

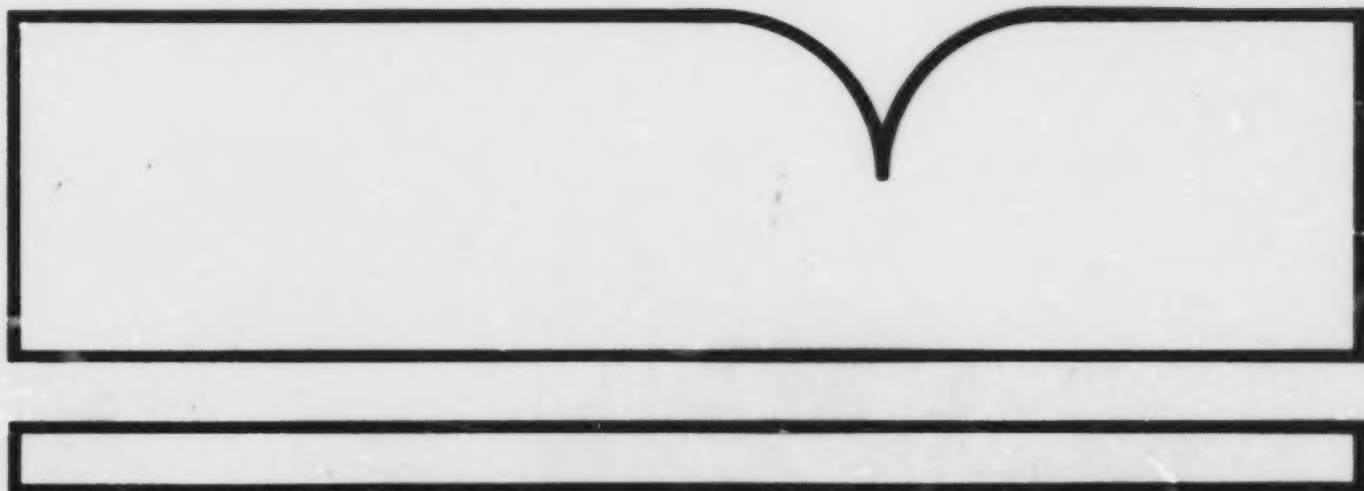
Critical Factors Controlling Vegetation
Growth on Completed Sanitary Landfills

Cook Coll.
New Brunswick, NJ

Prepared for

Municipal Environmental Research Lab.
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CRITICAL FACTORS CONTROLLING VEGETATION GROWTH
ON COMPLETED SANITARY LANDFILLS

by

Edward F. Gilman, Ida A. Leone and Franklin B. Flower
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New Brunswick, New Jersey 08903

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Grant No. R 805907-01

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MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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16. ABSTRACT This study identifies some of the critical factors that affect tree and shrub growth on reclaimed sanitary landfill sites and determine which woody species are adaptable to the adverse growth conditions of such sites. Trees planted at the Edgeboro Landfill, East Brunswick, New Jersey produced less shoot and stem growth and shallower roots than trees on the adjacent control plot. Of 19 woody species planted 4 years ago on a 14-year-old landfill, black gum and Japanese black pine proved to be the most tolerant and green ash and hybrid poplar the least tolerant to landfill conditions. Root systems of the more tolerant species proved to be shallower than those of the landfill intolerant species. Smaller planting stock (30-60 cm tall) appeared better suited for landfill planting than large trees (3-4 m tall). Balled and burlapped trees showed better growth on the landfill plot than bare-rooted material. Of five gas barrier systems tested, three proved effective: a soil trench underlaid by plastic sheeting over gravel and vented by means of vertical PVC pipes; a 0.9 m mound of soil underlaid with 30 cm of clay; and a 0.9 m soil-mound with no clay barrier.		
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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollution discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, and provides a most vital communication link between the researcher and the user community.

In many areas of the country, completed sanitary landfills have been converted into parks, golf courses, and recreational areas, and woody trees and shrubs have been planted on these areas in order to make them attractive. The field experiments reported here were designed to identify the critical factors controlling vegetation growth on such sites. The study included determination of the adaptability of woody species to the adverse soil environment on a completed refuse landfill and a study of planting techniques for these areas.

Francis T. Mayo, Director
Municipal Environmental Research
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This study identifies some of the critical factors that affect tree and shrub growth on reclaimed sanitary landfill sites and determine which woody species are adaptable to the adverse growth conditions of such sites. Trees planted at the Edgeboro Landfill, East Brunswick, New Jersey produced less shoot and stem growth and shallower roots than trees on the adjacent control plot. Of 19 woody species planted 4 years ago on a 14-year-old landfill, black gum and Japanese black pine proved to be the most tolerant and green ash and hybrid poplar the least tolerant to landfill conditions. Root systems of the more tolerant species proved to be shallower than those of the landfill intolerant species. Smaller planting stock (30-60 cm tall) appeared better suited for landfill planting than large trees (3-4 m tall). Balled and burlapped trees showed better growth on the landfill plot than bare-rooted material. Of five gas barrier systems tested, three proved effective: a soil trench underlaid by plastic sheeting over gravel and vented by means of vertical PVC pipes; a 0.9 m mound of soil underlaid with 30 cm of clay; and a 0.9 m soil-mound with no clay barrier.

This report was submitted in fulfillment of Contract No. R 805907-01 by Rutgers University under the sponsorship of the United States Environmental Protection Agency. The report covers the period June 1, 1978 to May 31, 1980, and the work was completed as of December 31, 1980.

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SECTION 1

INTRODUCTION

The sanitary landfill has been demonstrated to be the least expensive environmentally acceptable means of municipal waste disposal available to date, purportedly possessing the attribute of safety in addition to the relatively low cost. Though landfill sites may have originally been located at considerable distances from residential areas, rapid urban and suburban development in the United States has caused many once remote dumping grounds to be within developed areas. As such they provide an attractive source of much needed land for many purposes. Although conversion to recreational areas or other nonstructural usage has long been considered an acceptable end for completed landfill sites, the urgent need for space and for increased tax revenues has caused many municipalities to view completed landfills as acceptable for commercial use as well. In rural areas, intensifying land use has resulted in attempts to use completed landfills for growing commercial crops.

Regardless of the ultimate use of the landfill, certain serious disadvantages are inherent. Not the least of these are ecological upsets due to leaching of infiltrates and gases into groundwater, pollution of water supplies, production of toxic and explosive gas mixtures from anaerobic microbial decomposition of the organic matter present, and surface settlement. High ground temperatures have also been reported in the cover material of some completed refuse landfills.

Because abnormally high incidences of plant mortality were found on many landfills in New Jersey (Leone et al. 1977), it was desirable to determine if similar situations existed in other parts of the United States and to examine possible causes of and remedies for these vegetation growth problems. Reports from a nationwide mail survey funded by the USEPA, MERL, Solid and Hazardous Waste Division (Flower et al. 1978) determined that the scope of problems encountered when vegetating completed landfills was indeed of national magnitude. The landscaper, farmer and members of the general public would all benefit from successful vegetation projects such as parks, golf courses and recreational areas.

As urban population continues to grow, we can anticipate greater stimuli for converting former landfill sites into recreational areas and communities may be persuaded to convert these formerly unused lands into viable parks, golf courses and nature areas. Thus, it is vital to develop now the scientific knowledge required to perform these conversions. The goal of this project is to help develop these criteria through the accomplishment of the following tasks:

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1. To determine the relative adaptability of nineteen woody species to landfill conditions.
2. To determine if rooting depth is related to the relative tolerance of trees to the landfill soil environment.
3. To determine if small planting stock can survive on completed landfills better than large specimens.
4. To determine if balled and burlapped plant material is better suited for landfill plantings than bare rooted material.
5. To determine the effects of irrigation on tree growth in landfill soil.
6. To determine if leaf tissue nutrient contents of trees in landfill soil differs from the nutrient contents of trees in non-landfill soil.
7. To determine the effects of high landfill gas (CO_2 and CH_4) concentrations on availability of soil nutrients.
8. To determine the feasibility of constructing barriers to the passage of toxic gases from the refuse into the root zone of gas sensitive species.

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SECTION 2

CONCLUSIONS

SPECIES SELECTION

1. Woody species can be grown on completed sanitary refuse landfills.
2. The viability of woody vegetation in landfill conditions differs among species.
3. Rapidly growing trees appear to be more sensitive to landfill conditions than slow growers. However, since many of the rapidly growing trees (hybrid poplar cuttings, honey locust, red maple) produced more absolute growth on the landfill than the slow growers, rapid growers may be the more desirable species if one is not concerned about comparing growth on a landfill with the amount of growth normally produced on a non-landfill area.
4. Tree species planted as small seedlings appear better suited for landfill planting because they have the ability to quickly produce a shallow root system, whereas, larger sized saplings require more time to produce a shallow root system. A shallow root system may be more desirable because it allows roots to grow in a soil zone containing less landfill gas than the deeper soil zones close to the refuse.
5. Acid-loving plants (Japanese black pine, Norway spruce, black gum, bayberry) were more tolerant of landfill soil with a low pH (4.5) than of landfill soil with a higher pH (6.2).
6. Species tolerant to low oxygen environments (green ash, American sycamore, red maple, sweet gum, honey locust) did not tolerate landfill conditions as well as other species. Lack of sufficient soil moisture on the landfill soil was implicated as causing poor growth of these water loving species.
7. Species tolerance (based on comparisons of growth between landfill with growth on the control) differs according to shoot growth or stem area increase. Ginkgo, black gum, and Japanese yew were the most landfill tolerant species when shoot length was considered, whereas Japanese yew, white pine and Norway spruce were most tolerant when stem area increase was considered.
8. Low soil pH values (4.5) and high bulk densities (1.8 g/cc) may have predisposed several species (green ash, red maple, American sycamore) to

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the adverse landfill soil environment.

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9. An implication from these investigations is that if the study were to continue for several more years, some species which so far proved relatively intolerant to the landfill may eventually be regarded as tolerant because they may take longer to adapt to the landfill environment.

PREVENTING GAS MIGRATION INTO ROOT ZONES

1. Concentrations of carbon dioxide, oxygen and methane in the two mounds and gravel/plastic/vents trench were similar to those in the non-landfill control area indicating that these three gas barrier techniques are suitable for application in landfill vegetation projects.
2. American basswood trees growing in 0.9 m (36 in.) thick soil mounds (either unlined or lined with a 30 cm (12 in.) thick clay barrier) and in the gravel/plastic/vents trench generally produced more stem and shoot growth than trees in unmodified landfill soil. The other two trenches' gas-barrier systems did not promote better tree growth than the unmodified landfill areas.
3. American basswood in the gravel/plastic/vents trench and in the clay mound accumulated more of eight plant nutrients than trees in the unmodified landfill screening area.

EFFECTS OF SOIL FACTORS ON TREE GROWTH

1. Trees survived in landfill soil containing 3.9% CO₂, 0.4% methane and 18.8% O₂ but were killed in soil containing 22.8% CO₂, 12% CH₄ and 4.3% O₂. Trees cannot survive in soil containing these quantities of gas.
2. Irrigation significantly enhanced sugar maple growth in the landfill plot but not in the control.
3. When levels of CO₂, CH₄, O₂ and soil moisture in landfill soil change to levels not present in non-landfill soils, effects of these soil parameters on plant growth override the effects of the meteorological factors which normally affect tree growth.
4. Multiple regression analysis has shown that the soil environment on the landfill plot affected the ability of sugar maples to open and close their stomata. This may have caused some of the growth problems for trees on the landfill. However, on the control plot, meteorological factors appear to have affected stomatal changes in maple, whereas, the soil conditions had no effect.
5. Low soil moisture and high carbon dioxide (or low O₂) appear to have caused an increase in transpirational resistance and a decrease in growth of sugar maple on the landfill plot. This study presented evidence that changes in either one of these three factors alone while

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the other is held constant resulted in significant changes ($P < .05$) in transpiration and growth of sugar maples.

6. Regression analysis showed that soil nitrate, soil oxygen and soil temperature are the most important factors in determining basswood growth. However, this study has presented evidence that soil oxygen concentration and temperature may have influenced the soil nitrate concentration and hence, tree growth.

EFFECTS OF SOIL ENVIRONMENT ON LEAF TISSUE NUTRIENT CONCENTRATIONS

1. American basswood leaf tissue nitrogen, potassium and manganese concentrations were significantly lower and magnesium and iron significantly higher in the area of highest carbon dioxide and lowest oxygen concentrations (clay/vents trench) than in all other areas.
2. Inhibition of tree growth by low oxygen and/or high carbon dioxide may have resulted in the inability of American basswood to accumulate manganese, thus the higher soil manganese content in areas of poor growth. However, reduction of manganese oxides due to low oxygen (4.3%) may also have contributed to the high manganese content in the clay/vents trench.
3. Levels of soil oxygen at 30 cm, bulk density and the highest temperature during the growing season were significantly (positively) correlated with leaf uptake of nitrogen, potassium, magnesium, calcium, manganese, copper and iron.
4. Efficiency of nitrogen, potassium, magnesium, calcium, iron and copper accumulation by American basswood was considerably reduced ($P < .01$) for trees growing in the clay/vents trench where the average soil carbon dioxide concentration was 22.8% and soil oxygen 4.3% compared to all other areas on the landfill and control plots where carbon dioxide averaged 7.0% or lower and oxygen was 16.3% or higher.

GROWTH OF BALLED AND BURLAPPED VS BARE-ROOTED STOCK

1. Balled and burlapped sugar maples adapted better than bare-rooted maples to the soil conditions in the landfill plot.

ROOT ADAPTATIONS IN LANDFILL SOIL

1. Root systems of the more tolerant species (Japanese black pine, Norway spruce) were much shallower than those of the intolerant species on the landfill and control plots.
2. The root adaptation mechanism of hybrid poplar associated with landfill tolerance appeared to be different from that of green ash. Deep poplar

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- roots (30 cm) grew toward the soil surface and proliferated there, whereas, ash roots at the same depth did not extend to the soil surface. Instead, a shallow root system was provided for by roots sprouting from the root collar, 2 cm below the soil surface. The roots proliferated at this depth resulting in a shallow root system.
3. Wind-toppled trees may become more common on landfill sites due to the lack of deep anchor roots. A deeper soil cover may promote a deeper root system and therefore, help prevent wind toppling.
 4. The need for frequent irrigation on landfills becomes apparent since five of the six tree species were shown to produce a shallower root system on the landfill than on the control.
 5. Multiple regression analysis showed that soil carbon dioxide and oxygen together accounted for 84% of the variability in total root length of American basswood.
 6. Elevated levels of landfill soil carbon dioxide and methane in conjunction with low oxygen concentrations appear to be partially responsible for causing a decrease in total root length of American basswood and a reduction in the depth of maximum root penetration indicating a greater need for irrigation (at least 1"/wk) on completed landfills than non-landfill areas in order to maintain good tree growth.
 7. At high landfill gas concentrations 30 cm below the soil surface (22.8% CO₂, 12.0% CH₄, 4.3% O₂), American basswood roots did not maintain good growth; however, at moderate concentrations 8.1% CO₂, 0.9% CH₄, 18.5% O₂, the roots had the ability to grow toward the soil surface and avoid the contaminated soil environment at the 30 cm depth. Therefore, basswood roots appear to tolerate moderate landfill gas contamination not so much by growing in the contaminated soil, but by avoiding the gases through the production of a shallow root system.

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SECTION 3

RECOMMENDATIONS

SPECIES SELECTION

1. Since woody species differ in their adaptability to landfill soil, those charged with planting vegetation on completed landfills should avail themselves of current research on the adaptability of species to landfill conditions and avoid the use of nontolerant species.
2. Slow-growing trees appear to be better adapted to landfill conditions than rapid-growing trees.
3. Trees and shrubs planted as small specimens appear to be better adapted to landfill conditions than large specimens.
4. Species with a natural propensity for producing a shallow root are better suited for landfill vegetation projects than naturally deeper-rooted species.
5. Species reportedly tolerant to low oxygen environments will not grow well on landfills unless they are irrigated very thoroughly.
6. Balled and burlapped plant material appears to be better adapted than bare-rooted material to landfill soil.

PREVENTING GAS MIGRATION INTO ROOT ZONES

1. Landfill gases (primarily carbon dioxide and methane) must be kept away from the root system of trees and shrubs to promote good vegetation growth. Two methods proven effective are: a) a mound of soil (0.9 m) over existing cover and b) a lined and vented trench backfilled with suitable soil.

CRITICAL SOIL AMENDMENTS

1. Soil cover should be at least 0.6 m thick in order to promote good vegetation growth.
2. Landfill cover soil must be irrigated more frequently than non-landfill soil to promote good vegetation growth.

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3. Soil nutrient and pH levels should be periodically checked to insure against dangerously high or low levels.
4. In order to prevent the cover soil from becoming highly compacted during the closing of the landfill, organic matter such as composted sewage sludge, leaves or peat moss might be mixed with the cover material before it is spread over the refuse.

FUTURE INVESTIGATIONS

1. This study presented evidence that carbon dioxide, methane and oxygen concentrations and moisture content in the landfill soil affect stomatal resistance of sugar maple. Further investigations should be conducted into the effects of carefully controlled levels of CO_2 , CH_4 and O_2 and soil moisture on stomatal resistance to determine the degree of effect at various concentrations.
2. Additional controlled greenhouse studies are needed to ascertain the influence of soil gas levels on availability of soil nutrients and subsequent effects on plant growth.
3. Future screening studies should further test the hypothesis that rapidly growing trees are more sensitive to landfill soil pollution than slow growing trees.
4. Since rapidly growing trees draw more moisture from the soil and are thereby subjected to desiccation more quickly than are slow growers, the hypothesis that leaf antitranspirants slow the loss of moisture from the leaves and thereby enhance their landfill adaptability should be tested.
5. Further investigations of the effects of soil pH levels on species tolerance may be beneficial to our understanding of landfill vegetation growth.
6. Root investigations should be designed to determine if the adaptive capacity to produce a shallow root system in soil containing high concentrations of CO_2 and CH_4 differs among species.
7. Bare-rooted sugar maples appeared less suited than balled and burlapped maples for landfill plantings. Additional experiments should include a variety of species in order to determine if this relationship is universal or whether it is only characteristic of sugar maple.
8. Further in-depth studies of vegetation growth on former sanitary refuse landfills should include quantitative or qualitative investigations involving a number of other potentially toxic gaseous by-products of refuse decomposition such as ethylene, hydrogen sulfide and nitrous oxides.
9. Further experiments designed to test a variety of landfill gas-barrier

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- techniques should include replication of systems.
10. Additional shallow rooted species should be tested for their landfill tolerance.
 11. Future investigations of plant growth on and adjacent to landfill sites should study the effects of long-term, low level gas contamination of the root zone on the incidence of plant disease and insect damage.
 12. Procedures should be developed for spreading cover soil in a manner which does not cause high soil compaction.
 13. Large and small specimens of many species should be planted on several different landfills in order to verify the recommendation for planting small trees on landfills.
 14. Species screening experiments should include at least 20 replicates of each specie in each treatment.
 15. The minimum soil depth required for grass and tree growth over landfills entirely covered with plastic sheeting should be determined. This information may be applied to refuse and hazardous waste landfill sites.
 16. Leachate may be used for irrigation water in order to cut plant maintenance costs. However, leachates will vary with time and site and should be checked for undesirable characteristics.

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LITERATURE REVIEW

Many attempts to vegetate completed sanitary refuse landfills with trees and shrubs have been unsuccessful (Flower et al. 1978). The problems encountered during these projects have been identified (Flower et al. 1978). Gilman et al. (1980) have reported that tree and shrub species vary in tolerance to commonly occurring concentrations of landfill gases in the soil. Other detailed reports describing vegetation growth on landfills were not found in the literature.

EFFECT OF SOIL MOISTURE ON PLANT GROWTH

An important aspect of maintaining recently planted trees, shrubs and crops is assuring adequate soil moisture content in the root zone during the growing season. Rates of net photosynthesis decrease when plants are subjected to water stress (Troughton 1969). Direct effects of desiccation on the photosynthetic system (Troughton 1969) have been reported to cause shoot growth reductions in plum trees, leaf growth reduction in apple trees, fruit growth reduction in pear, and general growth reductions in many other fruit trees and field crops.

Fresh weight, dry weight and total root length of corn seedlings were reduced when either soil moisture or soil oxygen content was low (Gingrich and Russell 1957). Oxygen and moisture content interacted so that at high oxygen contents, growth was much reduced by low soil moisture; whereas at low oxygen contents, the growth difference between high and low soil moisture was insignificant (Gingrich and Russell 1957).

EFFECT OF ENVIRONMENTAL FACTORS ON LEAF TRANSPIRATION

Transpirational water loss is influenced by many plant factors such as leaf area, leaf anatomy, root:shoot ratio, stomatal frequency and control of stomatal aperture (Kramer 1933). Meteorological and soil parameters also have a marked effect on the stomatal changes in leaves. Meteorological and soil parameters on landfill areas are likely to be different than on non-landfill areas.

Transpiration measurements differ from leaf to leaf within a given tree. The temperature of sunlit leaves may be 10-15°C above air temperature and of shaded leaves, 1-2°C above air temperature. On days following substantial rainfall, stomata on sunlit leaves remain open; however, several days later,

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stomatal resistance for sunlit leaves is often higher than that of shaded leaves (Butler 1977).

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Experiments conducted with four oak species and sugar maple showed that when air temperature was increased from 20-35°C, stomata opened and transpiration increased (Wueuscher and Kozlowski 1971). In cocklebur (Xanthium pennsylvanicum) photosynthetic removal of carbon dioxide at increased light intensities was responsible for the opening of stomata (Mansfield and Heath 1961). Increasing the temperature during the night caused the stomata to open to a point comparable in magnitude to that in light of moderate intensity (Mansfield 1965). Meidner and Heath (1959) described two opposing effects of increasing air temperature on onion (Allium cepa) stomata: a closing effect which was shown to be due to accumulation of carbon dioxide in the leaf tissue and an opening effect when such accumulation was prevented.

A comparison was made by Davies and Kozlowski (1974) between stomatal opening and closing in response to changes in humidity. Seedlings of white ash and sugar maple were subjected to relative humidity changes from 20-80 percent at two light intensities (6,500 lux and 32,000 lux). Increases in humidity caused stomatal opening; decreases caused stomatal closure, as is normal for most plants. However, stomata were less affected by humidity changes at high than at low light intensities. These same phenomena have been reported for other species (Leyer and Stocker 1965). Experiments by Schulze et al. (1972) with three plant species differing completely in their ecological demands yielded basically the same results i.e. increased humidity opens stomata and lowering humidity closes stomata. Interactions between humidity and temperature effects on leaf resistance may partially explain conflicts in the literature concerning temperature effects on stomata as suggested by Schulze et al. (1972). One study indicates that stomata of orange may close when temperature is increased while relative humidity decreases; but that increasing temperature between 20-40°C may cause stomata of orange to open slightly, provided humidity remains constant (Hall et al. 1975). There has been no published literature on the effects of soil temperature on stomatal opening changes, and ultimately on growth for plants growing on landfill soils.

Soil moisture content was also found to interact with humidity in regard to stomatal resistance. Unirrigated Hammada scoparia plants were found to respond more quickly and to a greater degree to changes in air humidity than were irrigated plots (Schulze et al. 1972). In bean plants, stomatal conductance decreased with decreased air humidity; however, the reduction was greater at higher soil moisture contents (Moldau and Syber 1976).

Davies et al. (1969) report that increasing wind speed over a leaf surface causes variable responses in different plants. Transpiration over a 24-hour period was increased by wind in ash, decreased in maple, and unaffected in pine. These differences were reflected in stomatal control i.e. whereas maple stomata closed rapidly when exposed to wind, those of ash did not.

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EFFECTS OF SOIL CONDITIONS ON NUTRIENT UPTAKE

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Levels of soil nutrients available to plant roots may be affected by the soil atmosphere in sanitary landfill soil (Gilman 1978). Previous studies suggest that changes taking place in flooded soil generally parallel changes in landfill soil (Flower et al. 1978). Several soil elements e.g. manganese, iron, and sulfur become more available in flooded soil due to low oxygen levels (Ponnamperuma 1964). Higher available levels of these elements in the soil are often accompanied by their increased uptake by plant roots.

It has been shown since the early 1900's that plants grown in solution culture require both air and minerals in order to achieve adequate growth (Erickson 1946). There is a good deal of variability among plants in tolerance to low oxygen or high carbon dioxide concentrations and high soil temperatures in the root zone (Flower et al. 1978).

Soil compaction can also dramatically affect the response of plants to the soil environment by decreasing total pore space and by reducing the size of the pores. Veihmeyer and Hendrickson (1946a) found that the roots of sunflowers in the laboratory and grape vines in the field both penetrated a loam soil to the depth at which the bulk density reached 1.8 g/cm^3 , but would not penetrate any further where bulk density was higher. In a later paper, Veihmeyer and Hendrickson (1946b) reported that roots would not penetrate a loamy soil with bulk density above 1.9 g/cm^3 , whereas 1.6 to 1.7 g/cm^3 was the limiting value in clay soil. They attributed the failure of roots to penetrate soil with a bulk density above the critical (limiting) value to the size of the pores and not to the lack of oxygen, pointing out that roots can penetrate water-saturated noncompacted soils. In a compacted soil, roots of sugar cane were restricted to the top few inches; whereas in well structured soil, roots penetrated throughout the tilled horizon (Trowse and Hamber 1961). A bulk density of 1.12 g/cm^3 slightly reduced root penetration in sugar cane, a value of 1.36 g/cm^3 reduced root growth and caused rootlet distortions, and a value of 1.46 g/cm^3 seriously reduced root penetration. Sugar cane roots completely avoided growing into soils whose bulk densities exceeded about 1.52 g/cm^3 (Trowse and Hamber 1961). Parker and Jenny (1945) found that water infiltration of soil decreased as bulk densities increased, resulting in erosion and soil with a lower moisture content than that of a less compact soil.

The accumulation by plants of a number of nutrients is reportedly affected by poor soil aeration. Several authors have shown that potassium is the first mineral to decrease in leaf tissue under poor aeration (Broadbent and Stojanovic 1952; Hoagland and Broyer 1935; Lety et al. 1966). A suppressed soil oxygen supply to the roots of avacodo significantly decreased the leaf concentration of N, P, K, Ca, Mg and B (Labanauskas et al. 1968). Leyshon and Sheard (1974) found that low oxygen levels decrease N, P and K concentrations by 51, 61 and 58% respectively, and may account for reduced barley growth. Shoulders and Ralston (1975) reported that low oxygen levels attenuated the uptake of P, K, Ca and Mg in slash pine, but increased NO_3 uptake. In these studies high soil levels of methane, nitrogen, and carbon dioxide reduced phosphorus uptake to a greater extent than that of nitrogen and potassium. Phosphorus uptake was significantly reduced in leaves but

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increased in roots, suggesting an immobilization mechanism in roots. Since high soil carbon dioxide, nitrogen, and methane affected phosphorus uptake similarly in contrast to air, a lack of oxygen was suspected as the causal mechanism - not gaseous toxicity (Meiklejohn 1954; Niranjana and Mickleisen 1977).

Hammond et al. (1955) observed an interaction between oxygen and carbon dioxide when 5% carbon dioxide combined with 1% oxygen applied to corn roots resulted in the same potassium deficiency as treatment with 20% carbon dioxide and 20% oxygen. They concluded that soils associated with plants exhibiting potassium deficiencies, even though adequately supplied with potassium, often consist of heavy silt to silt-clay, have poor structure, are compacted by weather or are high in calcium.

Low soil oxygen alone or in conjunction with flooded soil has been associated with an increase in trace element contents (e.g. iron and sodium) in avocado seedlings (Labanauskas et al. 1968). Increased soluble levels of iron in some reduced soils have been reported to result in iron toxicity to crops (Howeler 1973; Ponnamperna 1955). The adverse effects on plants of high levels of available iron in reduced soils may result from direct toxicity; however, several reports in recent years suggest that the mechanism of iron toxicity may involve indirect effects of excess iron. Howeler (1973) postulated that excess soluble iron in flooded oxisols in Columbia may coat roots with an iron oxide barrier layer, thereby reducing nutrient transport from the soil into the plant. As a result, rice plants were assumed to be deficient in phosphorus, potassium, calcium, and magnesium as a result of iron accumulation in the root zone. Jones (1975) also suggested that reduced phosphorus uptake by some dune slack grass species may be attributed to phosphorus immobilization at the root surface due to the high level of iron associated with roots in waterlogged soils.

Waterlogged soils and sediments high in organic carbon content may become strongly reduced, resulting in sulfate reduction and sulfide accumulation. The detrimental effect of hydrogen sulfide on root function and plant growth is well established in the literature (Hollis 1967; Ponnamperna 1955; Vamos 1958). Several studies on the mechanisms of toxicity have indicated that the presence of hydrogen sulfide may also limit nutrient uptake (Hollis et al. 1975; Joshi et al. 1975). Ford (1965) Mitsui and Kumayawa (1964) suggested that the mechanism involved is an adverse effect of hydrogen sulfide on enzymatic reactions.

Few investigators have studied the effect of soil temperature on nutrient accumulation. Rattan (1974) reported a decrease in uptake by corn of nitrogen, potassium and zinc and in translocation of nitrogen at high soil temperatures. The requirement for calcium in wheat was found to increase with an increase in soil temperature from 20°C to 30°C (Burstrom 1956). Neilson (1971) also observed a greater plant response to the addition of calcium at higher soil temperatures (25-30°C) than at lower temperatures (15-20°C). Tissue content of N, P, K, Ca and Mg in corn, bromegrass and potato increased with increasing temperatures from 5°C to 19.5°C, above which total tissue nutrient content leveled off or decreased. During this investigation (Neilson 1971), high nutrient uptake at temperatures favorable for plant

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growth was greatly dependent on the amount of nutrients added to the soil medium. For example, total uptake of phosphorus by corn at 27°C without added phosphorus fertilizer was only 10% of that accumulated at this temperature with an N, P, K fertilizer treatment. A favorable temperature did not compensate greatly for lack of nutrients, nor did addition of nutrients offset the effect of unfavorable temperature.

EFFECTS OF SOIL CONDITIONS ON ROOT GROWTH

Information is available on the restriction of root growth by low soil oxygen supply (Leonard and Pinkard 1946), high carbon dioxide supply (Geisler 1963; Chang and Loomis 1945), mechanical impedance due to high soil compaction (Hopkins and Patrick 1969) and interactions among these parameters (Hopkins and Patrick 1969). These conditions often occur in landfill soil environments; however, studies describing root distribution in such areas are wanting. The studies presented herein characterize root systems growing in a sanitary landfill soil environment.

Most of the available information on the extent and concentration of forest tree root systems has been obtained by excavation and mapping exposed roots of seedlings or mature trees (Dean 1956; Pavlychenko 1937), and most of this work has been largely confined to species of pine, with relatively little attention to broadleaved deciduous trees. Such studies have largely dealt with three categories of root behavior: depth of penetration, tendency to concentrate, and lateral spread.

Lailtakari (1929) observed Scotch pine to be more shallowrooted on sandy soils than on loamy soils. Kaleda (1949) found that in individuals of this species growing in sandy soils, about 87% of the horizontal root system was located in the upper 8 inches. However, some secondary roots that originated from the taproot deep in the soil rose systematically to the surface (Lailtakari 1929). A similar situation was reported for bur oak by Weaver and Kramer (1933). The horizontal root distribution of white pine (Lutz et al. 1937) was found to be different in various soil horizons but the greatest development was always found in the upper (A horizon) soil layers.

One of the most intensively studies conifers in the United States with respect to root development is longleaf pine. Hodgkins (1977) reported that lateral root length and spread of this species increased with improved competitive position of the tree and with age up to maturity. Heyward (1933) observed that lateral roots of longleaf pine grew at a uniform depth throughout their length. Holch (1931) explained the pattern of heavy taproot plus prominent long laterals radiating at shallow depths from the taproot, described by (Lenhart (1934) and Wahlenburg (1946), as a characteristic of species adapted to drier sites.

Holch (1931) reported that the spread of roots of five species of deciduous trees greatly exceeded the height and spread of the tops. Kramer and Weaver (1933) observed that most of the major laterals of bur oak originated in the upper 2 feet of soil. The results of a study investigating morphological root characteristics of nine selected northeastern hardwoods

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(Stout 1956) revealed that the mean depth of the laterals was between 10 and 18 inches for four of the species while that of the other five species averaged less than 10 inches.

While investigating oak growth in the Arizona chaparral, Davis and Pace (1977) found live roots down to a depth of 21 feet.

Results of the above investigations show that many tree species develop relatively shallow root systems, although additional taproots extending down several feet are often found originating from laterals.

Studies on the tolerance of plants to waterlogging, many of which have been reviewed by Grable (1966), Gill (1970) and Rowe and Beardsell (1973), have been concerned with responses of root and shoot to lack of oxygen and to injurious chemical substances produced in the soil and in plant tissues, as well as with mechanisms of tolerance in certain species.

Periodic or permanent waterlogging is an important characteristic of many forest sites where Sitka spruce (*Picea sitchensis*) and lodgepole pine (*Pinus contorta*) are the species most frequently grown. On such sites, soil oxygen can decrease abruptly a short distance below the surface (Armstrong et al. 1976) and consequent injury to the root system results in shallow-rooted unstable crops. Field studies on Sitka spruce (Lees 1972) and lodgepole pine (Baggie 1972) growing on peat soils show that root development of both species is affected by waterlogging. Actively growing greenhouse-rooted lodgepole pine cuttings were more tolerant to waterlogging than spruce, when assessed in terms of the survival of both the tip and basal region of the root. By contrast, dormant roots of both species were so tolerant to waterlogging (28 days) that the tips remained alive and rapid regrowth took place after the soil was drained (Coutts and Philipson 1978).

During further investigations Coutts and Philipson (1978a) found that lodgepole pine roots penetrated to depths of 20 cm at 10°C in soil devoid of oxygen, whereas Sitka spruce made only shallow growth into the watertable. The results suggested that the deeper penetration of waterlogged soil by lodgepole pine than by spruce is due to internal oxygen transport in the pine roots. Philipson and Coutts (1978b) later showed that the pine had a greater capacity for oxygen transport to the flood-intolerant spruce.

Studies concerning the morphologic adaptations necessary for plants to withstand periods of anaerobiosis cite two types of modifications: i.e. increased branching of roots and the formation of adventitious roots. Geisler (1965) found that a reduction in the oxygen supply lead to a higher number of lateral roots per unit of root length and an enhancement in the density of the root system. As a consequence of increased root numbers, the area for active ion absorption located close to the root tips is increased (Brouwer 1965).

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Kramer (1951) postulated that the formation of shallow adventitious roots is an important modification for plants to survive oxygen depletion. The adventitious roots of some species contain more air space than the primary root systems, allowing oxygen to diffuse more freely down to the

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primary root system (Luxmoore 1969).

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Alberda (1953) observed that in rice, a mat of fine dense roots was formed at the surface of the water at the end of the tillering period. He suggested, and Voloras and Letey (1966) later demonstrated, that adventitious roots formed during aerobic conditions did not transport oxygen to the primary roots as effectively as did adventitious roots developed during anaerobiosis. Several deciduous tree species planted on mine spoil soil formed flat root systems, with virtually all root development in the surface and near surface layers (Zdzislaw and Greszta 1969). The authors imply that chemical properties of the soil can account for the development of shallow roots.

Research efforts aimed at establishing vegetation on completed sanitary landfills, let alone characterization of root systems growing in such environments, are limited. A study evaluating species adaptability to a landfill in California (1974) reports that root systems of the trees are shallow and lacking in strength. Reinhardt (1973) writes in the final report describing a refuse-milling project in Madison, Wisconsin, that when root systems are limited in extent and function by deficient moisture, deficient oxygen or high soil strength; fertilizers are apparently not utilized by the trees in sufficient quantities to cause measurable growth changes. Since neither of the above studies contain quantitative data, interpretation of these statements is difficult.

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In summarizing the results of an evaluation of 19 species to landfill environments, Gilman (1978) observed that woody plants growing in a landfill soil develop a greater proportion of their root system in the top 13 cm than the same species growing on a nearby non-landfill area. The need for a more thorough root distribution characterization in trees growing in landfill soil is clearly apparent in that the ability of a species to tolerate the landfill environment appears to be partially related to its ability to establish a shallow fibrous root system.

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SECTION 5

METHODS AND MATERIALS

TREE PLANTING

Species Screening Experiment

During the spring of 1976, 10 replicates of 19 woody species were planted on both the completed 14-year old Edgeboro sanitary refuse landfill located in East Brunswick, New Jersey and on a nearby non-refuse control area (Table 1). The species were evaluated during the 1976 and 1977 growing seasons for their ability to tolerate soil conditions present in the landfill soil (Gilman 1978). Data presented in this report were collected from the trees during 1978 and 1979 and compiled with portions of data collected during 1976 and 1977.

Gas-Barrier Techniques

During the spring of 1976, American basswood (Tilia americana) and Japanese Yew (Taxus cuspidata) were planted in replicates of six in each of seven gas-barrier areas: three trenches and two mounds on the landfill plot and one trench and one mound on the control plot (Gilman 1978; Leone et al. 1979). Following the removal of the basswoods and yew in the trench areas in the spring of 1978, two-year old black gum (Nyssa sylvatica), honey locust (Gleditsia triacanthos) and pin oak (Quercus palustris) seedlings were planted in replicates of six in the three landfill trenches and control trench and in the landfill and control unmodified areas.

TABLE 1. SPECIES SELECTED FOR VEGETATION GROWTH EXPERIMENT AT
EDGEBORO LANDFILL

Latin name	Common name
<u>Acer rubrum</u>	Red maple
<u>Euonymus alatus</u>	Euonymus
<u>Fraxinus lanceolata</u>	Green ash
<u>Ginkgo</u>	Ginkgo
<u>Gleditsia triacanthos</u>	Honey locust
<u>Liquidambar styraciflua</u>	Sweet gum
<u>Myrica pensylvanica</u>	Bayberry
<u>Nyssa sylvatica</u>	Black gum

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Latin name	Common name
<u>Picea excelsa</u>	Norway spruce
<u>Populus spp.</u>	Hybrid poplar (saplings)
<u>Populus spp.</u>	Hybrid poplar (from rooted cuttings)
<u>Plantanus occidentalis</u>	American sycamore
<u>Pinus strobus</u>	White pine
<u>Pinus thunbergi</u>	Black pine
<u>Quercus palustris</u>	Pin oak
<u>Rhododendron hyb. 'Roseum Elegans'</u>	Rhododendron
<u>Salix babylonica</u>	Weeping willow
<u>Tilia americana</u>	American basswood
<u>Taxus cuspidata var. capitata</u>	Japanese yew

Irrigation Effects on Tree Growth

To investigate the effects of irrigation on survivability of trees in landfills, thirty 2-year old sugar maple (Acer saccharum) seedlings spaced 1 m (39 in.) apart were planted in the spring of 1978 in two separate areas on both the landfill and control plots. One group of 30 trees on each plot was periodically irrigated during the 1978 and 1979 growing seasons according to the schedule presented in the irrigation section of this report. The other area was not irrigated and is referred to as the non-irrigated area in this report.

Effect of Size of Planting Stock on Species Tolerance to Landfills

To determine if the size of planting stock influences the ability of trees to survive in a landfill environment five 6-7 year-old, 2.5 m (98-in. tall) sugar maple saplings; ten 2-year-old 0.5 m (20-in. tall) sugar maple seedlings and ten 2-year-old green ash (Fraxinus lanceolata) 0.5 m (20-in. tall); were planted in the spring of 1978 on the landfill and control screening areas. Growth of the larger sized green ash planted in 1976 was compared with growth of the smaller ash trees to assess the effect of planting size on landfill survivability and growth.

Type of Planting Stock in Relation to Landfill Tolerance

In order to determine which type of planting stock is best suited for completed landfills five balled-and-burlapped (B&B) 2-3 m (79-118 in. tall), and five bare-rooted 2-3 m (79-118 in. tall) sugar maples were planted on the landfill and control screening areas in the spring of 1978.

CULTURAL METHODS

Fertilizing

In October 1977 and 1978, soil nutrient analyses for both plots indicat-

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ed low nitrogen, phosphorus and potassium levels. In order to raise these levels to an adequate range, on April 21-24, 1978 and April 25-26, 1979, 1.13 Kg (2.5 lbs) of 10-6-4 granular fertilizer were spread around each tree on all plots with a standard granular fertilizer spreader.

Liming

In order to raise the pH from approximately 5.0 to between 6.0 and 6.5, 0.57 Kg (1.25 lbs) of pulverized dolomitic limestone were applied to the soil around each tree on both plots by means of a walk-behind spreader on April 29, 1978. Since the pH did not rise to the desired level, application rates were recalculated and 1.8 Kg of additional limestone were applied on April 30, 1979. The pH was brought to the 6.2 level.

Irrigation

The rainfall in New Brunswick in the early spring of 1978 was sufficient to maintain the soil at a moisture level adequate for tree growth; but by the middle of May, the soil moisture had reached a level low enough to warrant irrigation. Soil moisture was tested by squeeze method. When water dripped from the soil when squeezed, it was classified as wet; when no water came out but the soil stayed together in a clump, the soil was moist; when the soil crumbled after squeezing, the soil was considered dry and the soil was irrigated. Approximately 39 L (10 gallons) of water were applied to all trees with a center-pivot irrigator during each irrigation period. Trees were irrigated four times during 1978.

Rainfall during the 1979 growing season was sufficient to warrant irrigation only twice during the summer. Approximately 39 L (10 gallons) of water were applied to each tree during irrigation periods.

During the investigation of the effects of irrigation on sugar maple growth, one group of 30 plants was irrigated in the landfill and control plots during the summer (1978 and 1979) so that the amount of water from rainfall and irrigation totaled approximately 2.5 cm (1 in.) per week. Plants were not irrigated if more than 2.5 cm (1 in.) of rain had fallen during a given week. Another group of 30 maples on each plot was not irrigated.

Pest Control

On May 7, 1978, pin oak, American basswood, weeping willow and hybrid poplar were sprayed with liquid Sevin for the control of tent caterpillars and canker worms which were present on some trees. A second spray was applied on May 23, 1978 for the same insect pests.

Red-headed pine saw flies were found on several Japanese black pine trees on the landfill plot during the week of August 7, 1978. The black pines on both plots were sprayed with Malathion on August 10 to control this pest.

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Rodent Control

In order to protect the bark and cambium of young seedlings from rabbit damage, 0.5 m (20 in.) high chicken wire was placed around areas which contained seedlings susceptible to rabbit injury.

Weed Control

During the 1978 growing season, grass and weeds were periodically cut with a power mower and weeds were pulled from the area immediately surrounding each tree trunk.

Weed growth in 1979 was chemically controlled. In April, three-eighths (3/8) cup of Roundup and one-half (1/2) cup of Princep were diluted with water to make three gallons of solution. This mixture was applied to the soil until the ground was thoroughly wet. This procedure was repeated in June.

SAMPLING METHODS

Soil Measurements

Soil gas content, temperature, bulk density, moisture content and nutrient concentrations were measured throughout the 1978 and 1979 growing seasons as described by Gilman (1978).

Tree Measurements

Shoot length and stem area (Table 2) are measured on each tree in the fall of 1978 and 1979 and root biomass was measured on each tree during the 1977 growing season. These procedures were presented in an earlier report, Gilman (1978) and Leone et al, (1979).

TABLE 2. DISTANCE FROM THE SOIL SURFACE AT WHICH STEM INCREMENT WAS MEASURED

Species		Distance from soil (cm)
Latin name	Common name	
<u>Acer rubrum</u>	Red maple	30
<u>Euonymus alatus</u>	Winged-euonymus	5
<u>Fraxinus lanceolata</u>	Green ash	30
<u>Ginkgo biloba</u>	Ginkgo	30
<u>Gleditsia triacanthos</u>	Honey locust	30
<u>Liquidambar styraciflua</u>	Sweet gum	8
<u>Myrica pennsylvanica</u>	Bayberry	3
<u>Nyssa sylvatica</u>	Black gum	8
<u>Populus sp.</u>	Hybrid poplar (saplings)	30
<u>Populus sp. m</u>	Hybrid poplar (rooted cuttings)	5

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Species		Distance from soil (cm)
Latin name	Common name	
<u>Picea glauca</u>	Norway spruce	3
<u>Platanus occidentalis</u>	American sycamore	30
<u>Pinus strobus</u>	White pine	5
<u>Pinus thunbergi</u>	Japanese black pine	5
<u>Quercus palustris</u>	Pin oak	30
<u>Rhododendron elegans</u>	Rhododendron	3
<u>Salix babylonica</u>	Weeping willow	30
<u>Tilia americana</u>	American basswood	30
<u>Taxus cuspidata capitata</u>	Japanese yew	3

Leaf Weight--

In order to measure the amount of leaf biomass produced by each American basswood on the seven gas-barrier areas and the landfill and control screening areas, four shoots were selected at random from each plant, one in each of the cardinal compass points (N, S, E, and W). From each of these four shoots, all the leaves were collected from last year's bud scale scar to this year's terminal bud and placed in four separate bags. The leaves were dried for approximately twenty-four hours at 65°C and weighed.

In order to measure average leaf weight of the sugar maples in the irrigation experiment, two leaves, i.e. about 10% of the total number, were randomly chosen from each tree. Leaves were dried for approximately 24 hours at 65°C in a forced air drying oven and weighed to the nearest milligram. Total leaf biomass produced by each tree was calculated by multiplying average leaf weight by the average number of nodes/shoot.

Tissue Nutrient Content--

On August 7, 1977, American basswood leaf tissue samples for elemental analysis were collected in the following manner: five shoots were randomly selected from each tree in each gas-barrier technique and landfill and control screening areas. Four leaves were collected from each shoot for a total of 20 leaves/tree. The leaves were dried for 24 hours at 40°C in a forced air drying oven, and ground through a 40 mesh screen. Chemical analysis of this tissue was determined according to methods presented in the Chemical Analysis portion of this report.

Transpiration Rate--

The physiological condition of the sugar maple seedlings planted for the irrigation experiments was monitored by measuring the rate of transpiration from a given area of leaf surface with a Lambda Instruments Diffusion Resistance Meter. Transpiration studies were designed for two purposes: the first was to investigate the transpirational strategy of sugar maple seedlings in the irrigated and non-irrigated areas on the landfill plot throughout an entire day and the second was to study the transpirational strategy over a period of days on the landfill and control plots.

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In the first experiment, five maples were randomly selected from the irrigated area where carbon dioxide averaged 2.3% and methane 0%; five from the non-irrigated area which contained 2.8% carbon dioxide and no methane; and five from another area in the non-irrigated area where carbon dioxide content was highest (7.8%) and methane was zero. Sugar maple was selected because of its reported sensitivity to landfills and flooding conditions (Leone et al. 1979). Diffusive resistance measurements were obtained from two leaves per tree starting at 8:30 a.m. and continuing at one hour intervals through the day until 8:30 p.m.

In the second experiment, ten trees were randomly selected from the irrigated and non-irrigated areas on both plots. Diffusive resistance was measured daily on two leaves per tree between 10 and 12 a.m. starting on August 9, and continuing through August 23, 1978.

Meteorologic Measurements

Air temperature and humidity data were obtained from the Rutgers University Meteorology Department for each hour during the day corresponding with the time of transpiration measurement. Wind speed and light intensity measurements were unobtainable because the weather station was being relocated during August 1978. Total wind movement (in miles per day) measurements were obtained for each day between August 9 and August 23.

CHEMICAL ANALYSIS

Nitrogen Content

Nitrogen content of American basswood leaf tissue was determined by the Kjeldahl method (Pepkowitz 1942).

Other Chemical Components

Leaf manganese, iron, potassium, magnesium, calcium, zinc and copper contents were determined by atomic absorption spectrophotometry.

ROOT EXCAVATION METHODS

Two replicates of black pine, Norway spruce and honey locust saplings and two replicates of hybrid poplar and green ash saplings and seedlings were selected for study at the end of the 1979 growing season from both the landfill and control screening areas for a total of 28 trees. At the end of the 1977 growing season, two American basswood (*Tilia americana*) trees were selected for study from each of three gas-barrier trenches on the experimental landfill plot, one gas-barrier system on the control plot and from the landfill and control unmodified areas totaling eight trees from the landfill plot and four from the control. The entire root system of each tree was completely excavated by means of a small hand trowel from the point of emergence at the main stump to the root tips. Each root greater than 1 mm in diameter was followed to its end except in cases where it lay beneath an

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adjacent tree or had been broken.

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After the individual roots had been exposed, the distance from the soil surface to the center of each root was measured at 30 cm (12 in.) intervals from the stump to and including the root tip.

STATISTICAL ANALYSIS

Analysis of variance, analysis of covariance, Student's "t" test, multiple regression, factor analysis, Chi-square analysis and correlation were used to analyze the data in this report (Zar 1974; Draper and Smith 1967; Harman 1977).

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SECTION 6

RESULTS

SPECIES SCREENING EXPERIMENT

Relative Viability of Plants

Twenty-three plants on the landfill plot and 19 on the control plot died between the winter of 1977-1978 and the end of summer 1979 (Table 3). Most of these deaths were attributed to dry soil conditions. In addition, the 10 weeping willows on the control plot were cut down in the spring of 1978 because all the willows on the landfill plot had died from lack of moisture by the end of the 1977 growing season. Ninety percent of the euonymus shrubs on both plots were destroyed by rabbits, therefore, the remaining shrubs were removed from both plots during the fall of 1978. All the rhododendron shrubs on the landfill plot had succumbed to exposure, winter injury or lack of moisture by the end of 1977. Enough replicates of sixteen of the original 19 species remained alive during 1978 and 1979 to statistically evaluate their ability to tolerate landfill soil conditions.

TABLE 3. NUMBER OF TREE DEATHS IN SCREENING EXPERIMENT BETWEEN NOVEMBER 1977 AND OCTOBER 1979

Species	Landfill plot	Control plot
Black gum	1	0
Bayberry	1	0
Pin Oak	1	0
Japanese yew	1	5
Sweet gum	5	3
Euonymus	3	9
Weeping willow	6	0
Japanese black pine	0	1
Hybrid poplar (saplings)	1	0
Ginkgo	3	0
Norway spruce	1	1
American basswood	0	0
Red maple	0	0
American sycamore	0	0
Hybrid poplar (rooted cuttings)	0	0
White pine	0	0

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TABLE 3. (continued)

Species	Landfill plot	Control plot
Honey locust	0	0
Green ash	0	0
Total	23	19

Relative Growth of Surviving Plants

During 1978, the majority of species grew better on the control plot than on the landfill plot (Tables 4 and 5) (Figures 1 and 2). Black pine was the only species which produced both greater shoot length and stem area on the landfill plot than on the control plot. Bayberry and ginkgo produced the same amount of shoot growth but greater stem area on the landfill plot than on the control plot. Norway spruce, white pine and black gum had better stem growth, but less shoot growth on the experimental landfill plot compared to the control. American basswood had slightly less stem growth and slightly greater shoot length on the landfill than the control. In hybrid poplar (rooted cuttings) stem growth was similar on the landfill and control plots, whereas, shoot length was greater on the control. Red maple had equal shoot growth on both plots but significantly poorer stem growth on the landfill compared to the control plot. In Japanese yew, American sycamore, pin oak, hybrid poplar, sweet gum, honey locust and green ash both shoot and stem growth were lower on the landfill than on the control plot.

TABLE 4. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1978 GROWING SEASON

Species	Shoot length (cm)		Landfill as % control	Landfill tolerance rank
	Landfill	Control		
Black pine	24.3	21.5	113.1	1
American basswood	9.1	8.4	108.8	2
Ginkgo	.8	.8	100.0	3
Bayberry	13.7	13.9	99.1	4
Red Maple	28.1	28.8	97.4	5
Japanese yew	13.2	14.5	90.9	6
American sycamore	25.4	30.6	83.0	7
Hybrid poplar (rooted cuttings)	95.7	121.0	79.1	8
Black gum	14.0	17.8	78.9	9
White pine	11.6	15.7	74.0	10
Pin oak	22.7	39.4	73.3	11
Norway spruce	14.9	22.7	65.3	12
Hybrid poplar (saplings)	41.2	103.5	39.8+	13

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TABLE 4. (continued)

Species	Shoot length (cm)		Landfill as % control	Landfill tolerance rank
	Landfill	Control		
Sweet gum	13.1	40.4	32.5 ⁺	14
Honey locust	17.6	61.1	28.8 ⁺	15
Green ash	10.4	40.6	25.7 ⁺	16

* Average from 1 to 10 replicates depending on species.

+ Significant @ P <.01.

† Significant @ P <.05.

TABLE 5. AVERAGE PERCENT STEM AREA INCREASE* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1978 GROWING SEASON

Species	Stem area (%*)		Landfill as % control	Landfill tolerance rank
	Landfill	Control		
Black pine	51.0	20.1	253.3 ⁺	1
Bayberry	18.8	8.1	232.5 ⁺	2
Norway spruce	27.9	12.2	228.5 ⁺	3
Ginkgo	14.8	8.4	175.0	4
White pine	23.9	20.1	118.9	5
Black gum	40.1	37.0	108.2	6
American basswood	26.4	27.2	97.0	7
Hybrid poplar (rooted cuttings)	188.7	198.7	95.0	8
Red maple	50.7	79.5	62.8 ⁺	9
Hybrid poplar (saplings)	133.2	216.7	61.4	10
Sweet gum	26.6	44.1	60.3	11
American sycamore	21.7	39.7	54.6	12
Green ash	37.9	73.6	51.6 ⁺	13
Pin oak	42.8	93.6	45.2 ⁺	14
Japanese yew	22.4	50.2	44.6 ⁺	15
Honey locust	29.2	86.5	32.8 ⁺	16

* Percent increase from March to October from 1 to 10 replicates depending on species.

+ Significant @ P <.01.

† Significant @ P <.05.

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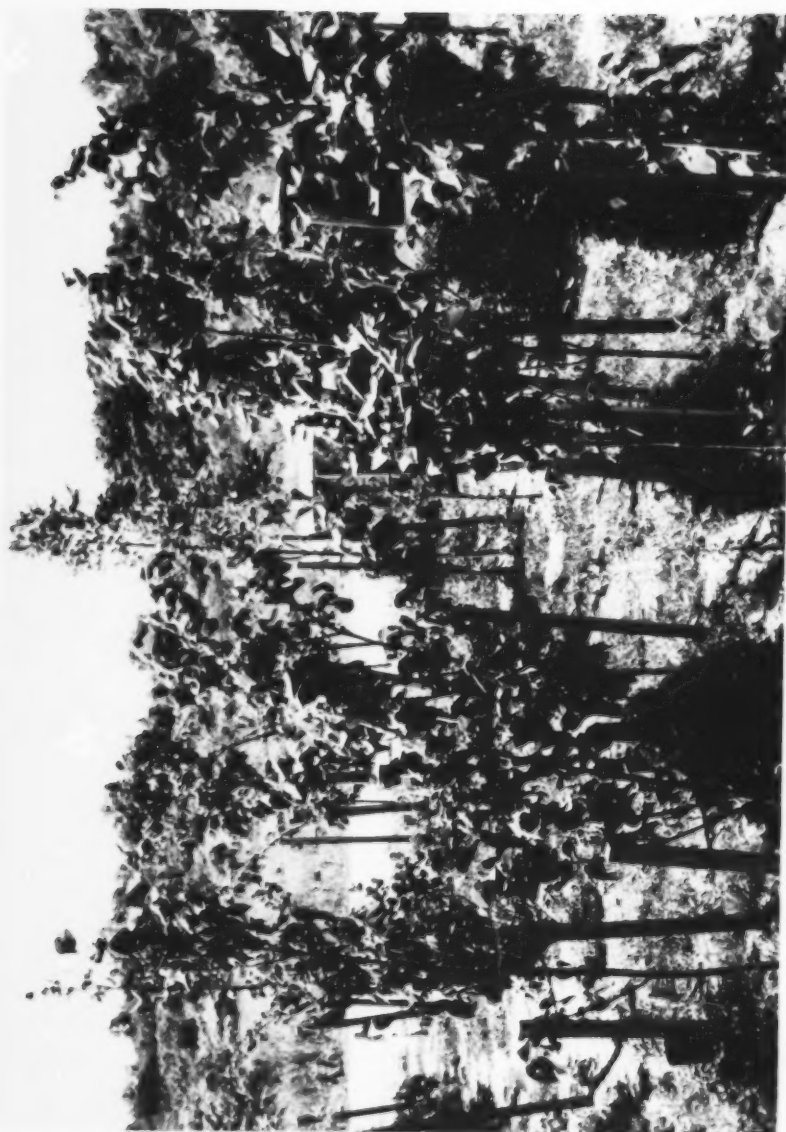


Figure 1. Portion of the landfill screening area.

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Figure 2. Portion of the control screening area.

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During 1979, six of the 16 species produced more shoot growth on the landfill than on the control plot; however, one-half of the species (8) produced more stem area on the landfill plot than on the control (Tables 6 and 7). Honey locust, hybrid poplar rooted cuttings and white pine produced greater shoot length and stem area on the landfill plot than on the control plot. Black gum, black pine and American sycamore had better shoot growth but poorer stem growth on the experimental landfill plot compared to the control. Japanese yew, bayberry, American basswood, red maple and pin oak increased cross-sectional stem area more on the landfill than on the control plot but produced less shoot length. Norway spruce, sweet gum, ginkgo, green ash and hybrid poplar saplings produced smaller amounts of shoot and stem growth on the landfill compared to the control plot.

TABLE 6. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1979 GROWING SEASON

Species	Shoot length (cm)		Landfill as % control	Landfill tolerance rank
	Landfill	Control		
Honey locust	101.8	85.5	118.8	1
Black gum	30.9	26.5	116.6	2
Hybrid poplar (rooted cuttings)	107.8	98.2	109.8	3
Black pine	27.6	25.5	109.4	4
White pine	20.1	19.1	105.6	5
American sycamore	51.7	49.3	104.8	6
Japanese yew	24.9	26.0	95.5	7
Norway spruce	24.9	26.6	93.6	8
Bayberry	12.0	13.8	86.9	9
American basswood	18.7	23.7	79.2	10
Red maple	48.6	61.6	78.8†	11
Sweet gum	35.7	48.9	73.1	12
Ginkgo	0.5	0.8	70.0	13
Pin oak	29.3	43.1	67.8	14
Green ash	34.1	59.5	57.4+	15
Hybrid poplar (saplings)	42.1	107.2	39.3+	16

* Average from 1 to 10 replicates depending on species.

+ Significant @ P < .01.

† Significant @ P < .05.

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TABLE 7. AVERAGE PERCENT STEM AREA INCREASE* FOR 16 SPECIES ON LANDFILL AND CONTROL PLOTS FOR 1979 GROWING SEASON

Species	Stem area (%*)		Landfill as % control	Landfill tolerance rank
	Landfill	Control		
Japanese yew	62.4	38.5	161.9+	1
White pine	52.0	33.0	157.8+	2
Red maple	121.8	85.9	141.8+	3
Bayberry	31.3	23.1	135.6	4
Honey locust	142.8	105.3	135.6	5
Hybrid poplar (rooted cuttings)	130.3	104.4	124.8	6
American basswood	78.9	64.5	122.3	7
Pin oak	73.3	68.8	106.5	8
Norway spruce	39.5	41.5	95.1	9
Black pine	53.3	57.5	92.7	10
Ginkgo	13.2	16.7	79.2	11
American sycamore	48.1	62.4	77.2†	12
Sweet gum	62.0	85.2	72.7+	13
Green ash	43.7	61.3	71.3+	14
Black gum	41.2	70.0	58.9+	15
Hybrid poplar (saplings)	55.0	127.0	43.3+	16

* Percent increase from March to October from 1 to 10 replicates depending on the species.

+ Significant @ P <.01.

† Significant @ P <.05.

Assessing the ability of each species to tolerate or adapt to the landfill environment by compiling growth data from the first four years of experimentation can be approached in several ways.

First, total shoot growth for each species on both plots was calculated by totaling shoot length measurements for each replicate for the years 1976, 1977, 1978 and 1979. Average values for all replicates are presented in Table 8. Each species was ranked in order of relative tolerance to landfill conditions on the basis of the ratio of values for landfill growth to those of control. The highest values for total shoot growth on the landfill as percent of control were obtained for ginkgo (127.5%) and black gum (117.3%) whereas, the lowest tallies corresponded to sweet gum and hybrid poplar saplings.

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TABLE 8. AVERAGE SHOOT LENGTH* FOR 16 SPECIES ON THE LANDFILL AND CONTROL PLOTS FROM 1976 THROUGH 1979 GROWING SEASON

Species	Landfill (cm)	Control (cm)	Landfill as % of control	Landfill tolerance rank+
Ginkgo	25.5	20.0	127.5	1
Black gum	92.9	79.2	117.3	2
Japanese yew	69.8	70.1	99.6	3
American sycamore	133.6	135.7	98.4	4
Japanese black pine	83.8	90.7	92.5	5
Hybrid poplar (rooted cuttings)	320.6	354.1	90.5	6
Bayberry	49.8	57.4	86.7	7
White pine	53.8	65.0	82.7	8
Norway spruce	56.6	69.8	81.1	9
American basswood	52.0	67.6	76.9	10
Red maple	111.0	150.4	73.8	11
Pin oak	77.2	115.8	66.7	12
Honey locust	135.6	217.7	62.3	13
Green ash	81.5	144.4	56.4	14
Sweet gum	65.8	128.3	51.3	15
Hybrid poplar (saplings)	76.0	331.5	22.9	16

* Each number is the sum of shoot length measurements from each living replicate from the years 1976, 1977, 1978 and 1979 from 1 to 10 replicates per species.

+ The lower the number, the more tolerant the species is to landfill conditions.

Secondly, average stem area increase from March 1977 to the end of 1979 was computed for each species on both plots (Table 9). Each species was ranked in order of relative tolerance to the landfill environment with the highest rank given to that species which grew best on the landfill compared to the control and the lowest rank corresponding to that species which grew poorest on the landfill compared to the control plot. The highest values for stem increase on the landfill as percent on control were obtained for Japanese yew (176.2%) and white pine (133.0%) whereas, the lowest tallies corresponded to hybrid poplar saplings (39.5%) and green ash (37.7%).

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TABLE 9. PERCENT STEM CROSS-SECTION AREA INCREASE* FOR 16 SPECIES FROM MARCH 1977 THROUGH OCTOBER 1979 ON THE LANDFILL AND CONTROL PLOTS

Species	Landfill (%)	Control (%)	Landfill as % of control	Landfill tolerance rank ⁺
Japanese yew	188.4	106.9	176.2	1
White pine	174.0	130.8	133.0	2
Norway spruce	164.9	127.5	129.3	3
Black gum	641.7	539.5	118.9	4
Japanese black pine	275.3	233.8	117.8	5
American basswood	165.5	153.4	107.6	6
Ginkgo	25.8	29.9	86.3	7
Red maple	393.7	468.4	84.0	8
Bayberry	96.3	119.0	80.9	9
American sycamore	171.7	255.3	67.2	10
Pin oak	361.9	650.0	55.7	11
Honey locust	291.4	620.9	46.9	12
Sweet gum	307.7	731.6	42.0	13
Hybrid poplar (rooted cuttings)	9,534.5	23,993.4	39.7	14
Hybrid poplar (saplings)	295.0	1,165.8	39.5	15
Green ash	130.2	345.6	37.7	16

* Stem measurements from 1 to 10 replicates, depending on the species.

+ The lower the number, the more tolerant the species is to landfill conditions.

Thirdly, rank values for shoot growth during 1976, shoot and stem growth in 1977 (both given in a previous report¹), shoot and stem growth during 1978 (Tables 4 and 5) and shoot and stem growth during 1979 (Tables 6 and 7) were totaled for each species (Table 10). The values were aligned from lowest to highest with the most tolerant species (Japanese yew) represented by the lowest sum of tolerance ranks value and the species most sensitive to the landfill environment (hybrid poplar saplings) at the bottom of the table with the highest value.

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¹ EPA Publication 600/2-79-128. Adapting Woody Species and Planting Techniques to Landfill Conditions.

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TABLE 10. SUM OF LANDFILL TOLERANCE RANKS* FOR SHOOT AND STEM MEASUREMENTS FROM 1976 THROUGH 1979

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Species	Sum of tolerance rank values ⁺	Landfill tolerance rank
Japanese yew	37	1
Japanese black pine	42	2
Black gum	45	3
Bayberry	45	3
Ginkgo	46	5
White pine	49	6
Norway spruce	50	7
Hybrid poplar (rooted cuttings)	50	7
American basswood	54	9
American sycamore	60	10
Red maple	60	10
Honey locust	72	12
Pin oak	77	13
Sweet gum	83	14
Green ash	87	15
Hybrid poplar (saplings)	102	16

* Each number is the sum of that species' rank in 7 rank lists relative to the other species. The 7 rank lists are the following: stem area increase measurements from 1977, 1978 and 1979, and shoot length measurements from 1976, 1977, 1978 and 1979.

+ The lower the number, the more tolerant the species is to landfill conditions.

Finally, the Principal Axis Factor Method (Harmen 1967) was used to calculate average factor scores for each species on both plots (Table 11). The nature of this statistical procedure dictates that the final factor scores must add up to zero, thus, the presence of negative numbers in the table. The difference between the control and landfill plots was computed for each species. The species with the largest negative difference were ranked as the most tolerant to the landfill environment because a negative value indicated that growth was better on the landfill than on the control plot. The species with the largest positive difference (Hybrid poplar rooted cuttings) was rated as least tolerant of the landfill soil environment because growth on the landfill plot compared to the control was poorer than any other species.

The grand total of the landfill tolerance ranks for each species computed by summing the rank values from each of the above four methods of analyzing the compiled growth data is presented in Table 12. This composite ranking order identified black gum as the most landfill tolerant woody species of those tested.

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TABLE 11. AVERAGE FACTOR SCORES* FOR 16 SPECIES FROM DATA FROM 1976 THROUGH 1979 ON THE LANDFILL AND CONTROL PLOTS

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Species	Landfill	Control	Difference (control-landfill)	Landfill tolerance rank ⁺
Black gum	-0.02	-0.14	-0.12	1
Japanese black pine	-0.23	-0.28	-0.05	2
Bayberry	-0.65	-0.69	-0.04	3
Ginkgo	-1.08	-1.11	-0.03	4
White pine	-0.61	-0.63	-0.02	5
American basswood	-0.57	-0.54	-0.03	6
Norway spruce	-0.57	-0.50	-0.07	7
Japanese yew	-0.43	-0.36	-0.07	8
Sweet gum	0.18	0.31	0.13	9
American sycamore	0.02	0.17	0.15	10
Red maple	0.15	0.53	0.38	11
Pin oak	-0.22	0.36	0.58 [†]	12
Hybrid poplar (saplings)	0.12	0.71	0.59 [†]	13
Green ash	-0.57	0.30	0.87 [†]	14
Honey locust	0.31	1.33	1.02 [†]	15
Hybrid poplar (rooted cuttings)	2.96	4.04	2.96 [†]	16

* Principal Axis Factor Method was used to calculate factor patterns and factor scores for shoot and stem data from 1976 through 1979.

+ The lower the number, the more tolerant the species is to landfill conditions.

[†] Significant @ P < 0.05.

TABLE 12. RELATIVE TOLERANCE OF 16 SPECIES TO LANDFILL CONDITIONS*

Species	Sum of landfill tolerance rank values
Black gum (4, 8) ⁺ -R ^Δ	10
Japanese yew (9, 4) -	13
Japanese black pine (10, 9) -	14
Ginkgo (7, 9) -S	17
White pine (10, 10) -S	21
Bayberry (9, 9) -	23
Norway spruce (8, 8) -S	26
American basswood (9, 10) -S	31
American sycamore (10, 10) -R	34
Red maple (9, 10) -I	41
Hybrid poplar (rooted cuttings) (10, 5) -R	44

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Species	Sum of landfill tolerance rank values
Pin oak (9, 10) -R	48
Sweet gum (1, 6) -R	51
Honey locust (10, 10) -R	52
Green ash (10, 10) -R	59
Hybrid poplar (saplings) (2, 7) -R	60

- * Tolerance was established by totaling the landfill tolerance rank values for each species from Tables 8, 9, 10 and 11.
- + Number of replicates living on the landfill and control plots respectively at the end of 1979.
- Δ R=rapid growth rate, I=intermediate growth rate, S=slow growth rate, N=data not available - from Fowells (1965).

The variation between trees in total shoot growth and percent stem growth is represented for each species on both plots by the coefficient of variation (Tables 13 and 14). This statistic expresses sample variability relative to the mean of that sample by dividing the standard deviation by the mean value. There was less variability in both shoot and stem growth among landfill tolerant species on the landfill than on the control. However, the variability among replicates of those species relatively sensitive to the landfill soil conditions, i.e., those towards the bottom of Tables 13 and 14, was generally greater on the landfill than on the control plot.

Total shoot growth and stem diameter increase are presented in Table 15 in descending order from the highest growth on to the least amount of growth on the landfill. According to this list, hybrid poplar (from rooted cuttings) was the best total growth species, and ginkgo the least total growth species for planting on completed landfill sites.

TABLE 13. COEFFICIENTS OF VARIATION* FOR TOTAL SHOOT LENGTH FROM 1976 THROUGH 1979 OF 16 SPECIES+ ON LANDFILL AND CONTROL PLOTS

Species	Landfill	Control
Black gum	28.0	35.0
Japanese yew	24.0	33.6
Japanese black pine	23.6	30.7
Ginkgo	0.0†	4.4
White pine	34.5	38.5
Bayberry	43.7	35.7
Norway spruce	31.7	39.3

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Species	Landfill	Control
American basswood	37.7	51.0
American sycamore	26.0	23.7
Red maple	33.1	32.8
Hybrid poplar (rooted cuttings)	22.8	17.8
Pin oak	29.4	17.9
Sweet gum	0.0 ^Δ	9.0
Honey locust	25.0	20.9
Green ash	39.0	18.0
Hybrid poplar (saplings)	31.2	19.1

* Coefficient of Variation = $\frac{\text{standard deviation}}{\text{mean}}$ X 100.

+ Species are listed from most tolerant to least landfill tolerant as given in Table 12.

† There was no variation in the data points.

Δ Only one tree living so standard deviation = 0.

TABLE 14. COEFFICIENTS OF VARIATION* FOR PERCENT STEM INCREASE FROM 1977 THROUGH 1979 FOR 16 SPECIES[†] ON LANDFILL AND CONTROL PLOTS

Species	Landfill	Control
Black gum	41.3	46.8
Japanese yew	38.8	56.0
Japanese black pine	45.1	55.1
Ginkgo	50.2	102.6
White pine	45.4	63.8
Bayberry	31.1	51.1
Norway spruce	52.4	46.2
American basswood	29.6	57.8
American sycamore	230.9	41.9
Red maple	74.8	28.2
Hybrid poplar (rooted cuttings)	62.6	39.0
Pin oak	33.9	38.6
Sweet gum	0.0 [#]	42.0
Honey locust	38.8	58.4
Green ash	41.5	37.4
Hybrid poplar (saplings)	39.1	32.7

* Coefficient of Variation = $\frac{\text{Standard deviation}}{\text{mean}}$ X 100.

+ Species are listed from most tolerant to least landfill tolerant.

Only one tree living so standard deviation = 0.

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TABLE 15. TOTAL SHOOT LENGTH* AND PERCENT STEM INCREASE+ FOR 16 SPECIES ARRANGED IN DESCENDING ORDER OF VALUES FROM 1976-1979 ON THE LANDFILL

Species	Shoot length (cm)	Species	Stem increase (%)
Hybrid poplar (rooted cuttings)	320.6	Hybrid poplar (rooted cuttings)	9534.5
Honey locust	135.6	Black gum	641.7
American sycamore	133.6	Red maple	393.7
Red maple	111.0	Pin oak	361.9
Black gum	92.9	Sweet gum	307.7
Japanese black pine	83.8	Hybrid poplar (saplings)	295.0
Green ash	81.5	Honey locust	291.4
Pin oak	77.2	Japanese black pine	275.3
Hybrid poplar (saplings)	76.0	Japanese yew	188.4
Japanese yew	69.8	White pine	174.0
Sweet gum	65.8	American sycamore	171.7
Norway spruce	56.6	American basswood	165.5
White pine	53.8	Norway spruce	164.9
American basswood	52.0	Green ash	130.2
Bayberry	49.8	Bayberry	96.3
Ginkgo	25.5	Ginkgo	25.8

* Each number is the sum of the average shoot length measurements from each living replicate for the years 1976 through 1979.

+ Percent increase from March 1977 through 1979.

Soil Measurements

Measurements of numerous soil variables throughout the study were made in order to characterize the nature of the stress to which the plants were subjected on the landfill plot and to compare the values for these variables with those in the control plot (Table 16). Mean CO₂ and CH₄ content and temperature were significantly greater (P<.01) and O₂ and moisture content significantly lower on the landfill plot than on the control plot. Concentrations of CO₂ and CH₄ on the landfill plot were significantly higher at the deeper soil depths, (i.e. 90 cm) than in surface layers and O₂ readings were significantly lower at the 90 cm depth than at more shallow depths (Table 17). The levels of all soil nutrients except zinc and manganese were lower on the landfill plot than on the control plot, but not significantly so.

Carbon dioxide, O₂ and CH₄ concentrations at the 20 cm depth were all highly correlated with each other during the period 1977 through 1979 (Table 18). Levels of each of the soil gases were also significantly correlated with temperatures recorded at the 20 cm depth in the soil.

TABLE 16. MEAN VALUES* FOR SOIL VARIABLES ON LANDFILL AND CONTROL PLOTS IN 1978 AND 1979

Soil Variable	Landfill plot		Control plot	
	1978	1979	1978	1979
Temperature °C	19.0b ⁺	18.6b	17.7a	17.3a
% Moisture content	8.0a ⁺	10.1b	10.8bc	12.2c
Conductivity (1-2)	0.1	0.1	0.1	0.1
Organic matter %	1.8	1.8	2.3	2.1
% Sand	82.8	83.1	79.0	75.1
pH	4.5	6.1	4.5	5.9
lbs/A				
Mg	37	62.3	114	124.1
P	79	147.7	60	141.1
K	123	105.7	241	135.0
Ca	178	1591	567	2036
NO ₃	29.7	16.7	80	36.0
NH ₄	10	9.7	22	14.0
ppm				
Fe	79	65.5	153	75.5
Cu	4.1	2.9	4.7	3.9
Zn	7.5	5.4	4.3	7.7
Mn	19	14.2	17	31.5
B	0.30	0.24	0.25	0.29

* Samples collected at the 20 cm depth. Each gas concentration value is the mean of 320 readings.

+ Row means followed by different letters are significantly different at P<.01.

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TABLE 17. SOIL GAS CONCENTRATIONS DURING 1978 AND 1979 AT THE 20 cm^{*}, 60 cm⁺ AND 90 cm⁺ DEPTHS ON THE LANDFILL AND CONTROL PLOTS

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Soil Depth (cm)	Year	Landfill			Control		
		%O ₂	%CO ₂	%CH ₄	%O ₂	%CO ₂	%CH ₄
20	1978	18.1b [#]	3.8a	0.4a	20.0b	1.2b	0.0a
	1979	17.2b	4.1a	0.4a	19.8b	0.9a	0.0a
60	1978	18.1b	6.7b	1.8b	18.2a	1.2b	0.0a
	1979	18.3b	8.7b	1.7b	18.8a	1.2b	0.0a
90	1978	12.7a	24.9d	16.9d	18.3a	1.3b	0.0a
	1979	13.7a	22.1c	14.2c	18.9a	1.2b	0.0a

* Values represent mean from 640 readings on the landfill plot and 80 readings on the control plot during 1978 and 1979.

+ Values represent mean from 120 readings on the landfill plot and 40 readings on the control plot during 1978 and 1979.

Column means followed by different letters are significantly different from each other @ P<.01.

TABLE 18. CORRELATION^{*} AMONG SOIL GASES⁺ AND SOIL TEMPERATURES ON THE LANDFILL PLOT

Gas	Carbon dioxide	Methane	Temperature
Oxygen	-0.98 [#]	-0.95 [#]	-0.72 [#]
Carbon dioxide	--	+0.94 [#]	+0.72 [#]
Methane	--	--	+0.71 [#]

* Each number represents the correlation coefficient (r) between the two indicated soil parameters for data collected during 1977, 1978 and 1979.

Significant at P<0.01.

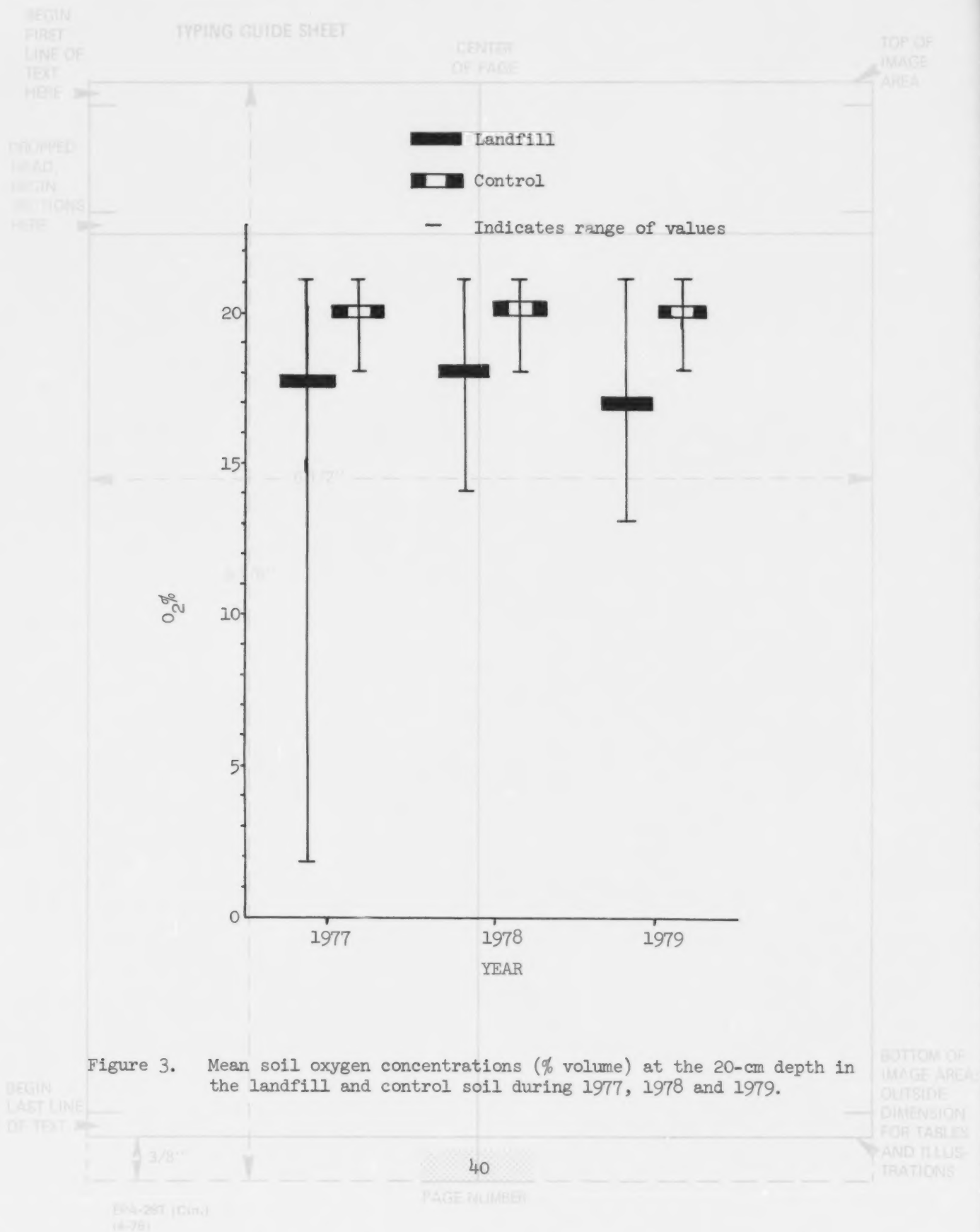
+ Samples collected at the 20 cm depth. Each value was computed on 960 readings.

Variability around the mean CO₂, O₂ and CH₄ concentrations was greater in the landfill soil than in the control soil demonstrating that high levels were occasionally recorded in the landfill soil (Figures 3, 4 and 5).

Soil pH values in the landfill soil differed very little from levels in the control soil (Figure 6). The pH dropped from approximately 5.0 in 1977 to 4.5 in 1978 on both plots only to rise to 6.2 and 6.3 (control and landfill respectively) when the soil was amended with proper amounts of limestone.

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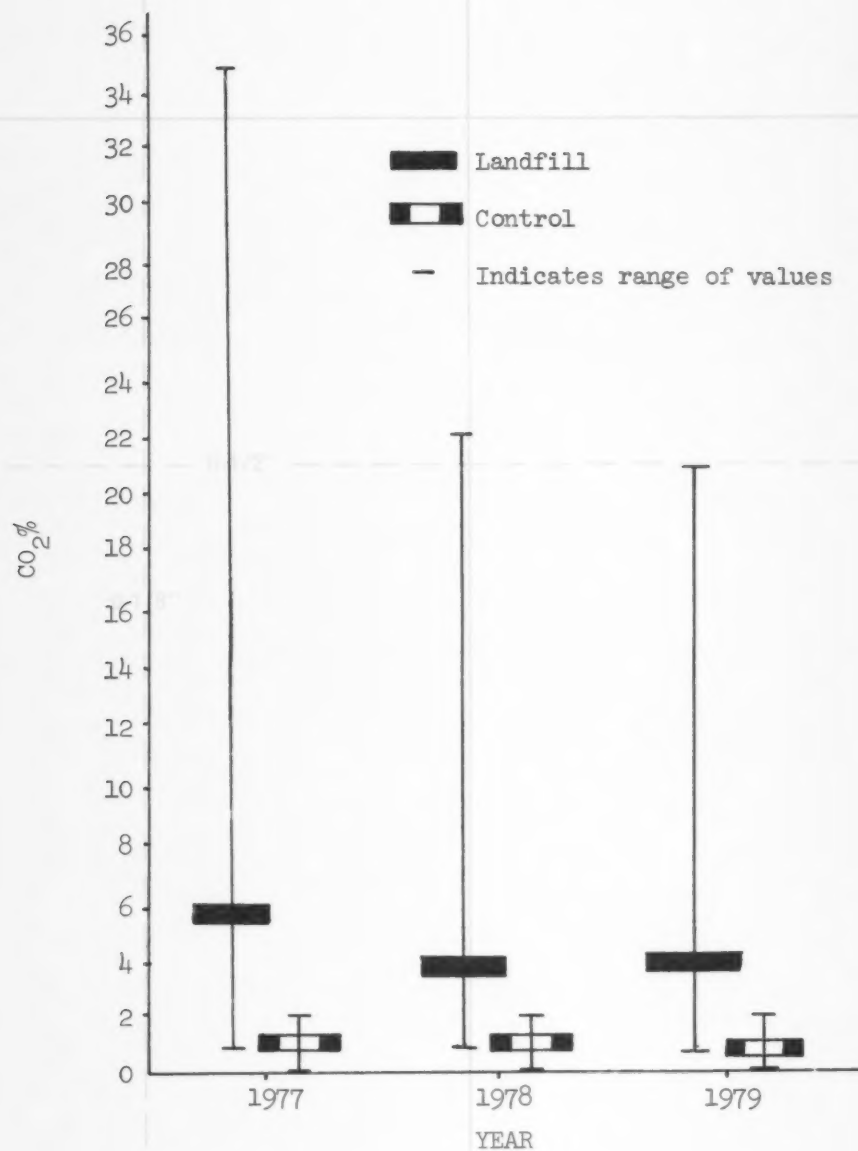


Figure 4... Mean soil carbon dioxide concentrations (% volume) at the 20-cm depth in the landfill and control soil during 1977, 1978 and 1979.

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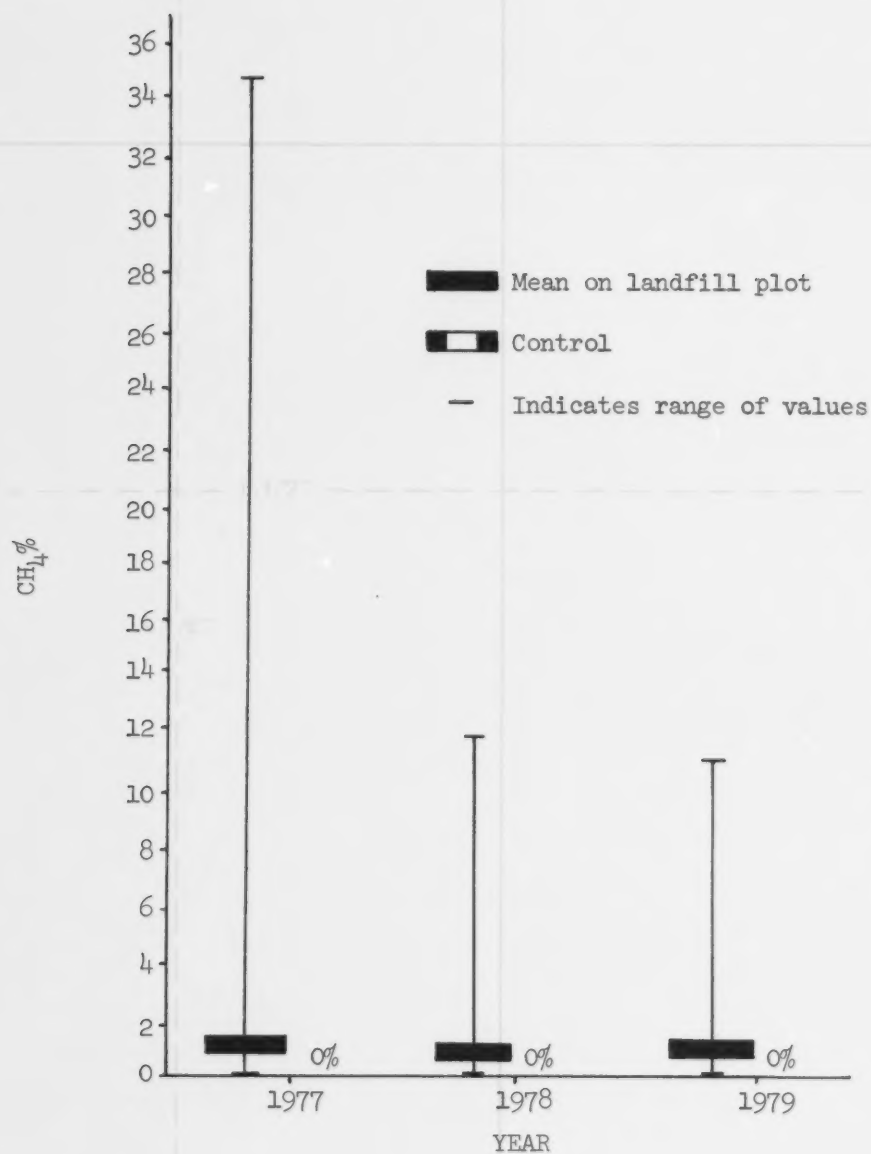


Figure 5. Mean soil methane concentrations (%volume) at the 20-cm depth in the landfill and control soil during 1977, 1978 and 1979.

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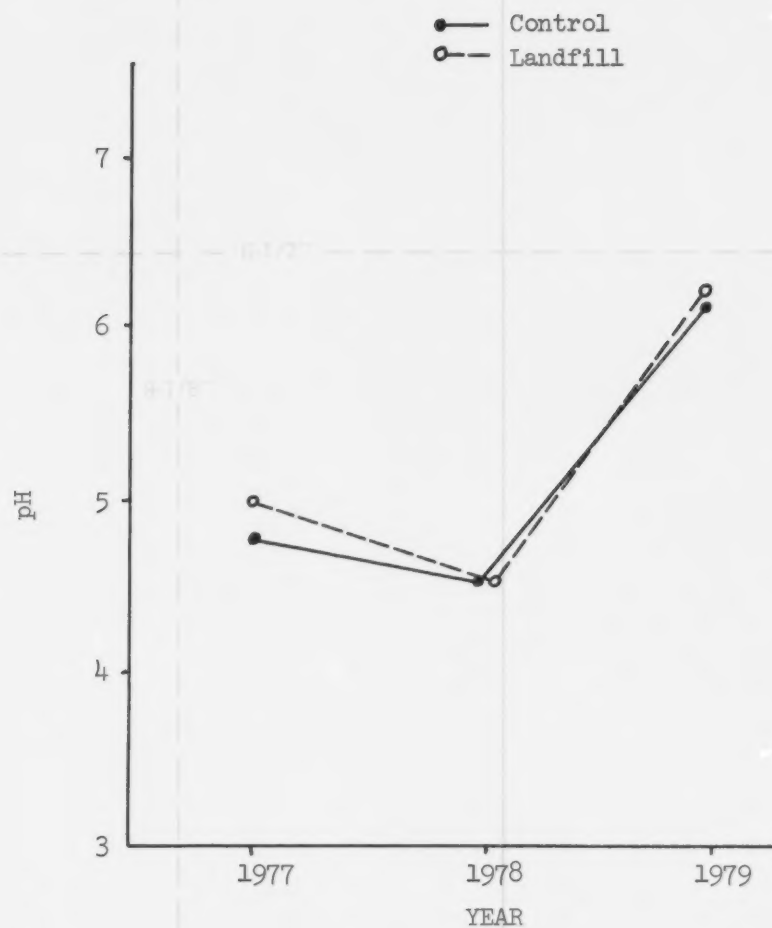


Figure 6. Soil pH levels during 1977, 1978 and 1979.

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TABLE 19. SOIL VARIABLES WHICH CORRELATE WITH SHOOT AND STEM GROWTH OF SPECIES IN THE LANDFILL SPECIES SCREENING EXPERIMENT*

Species	Shoot Growth	
	Soil Variables	
Black pine	None	
American basswood	M.C. ⁺ , B.D., O ₂ *M.C., O ₂ *B.D.	
Ginkgo	None	
Bayberry	None	
Red maple	None	
Japanese yew	None	
American sycamore	M.C., B.D., O ₂ *M.C., O ₂ *B.D.	
Hybrid poplar (rooted cuttings)	None	
Black gum	O ₂ , B.D., O ₂ *M.C.	
White pine	None	
Pin oak	None	
Norway spruce	O ₂	
Hybrid poplar (saplings)	None	
Sweet gum	O ₂ , M.C., B.D., O ₂ *M.C., O ₂ *B.D.	
Honey locust	O ₂ , M.C., B.D., O ₂ *M.C., O ₂ *B.D.	
Green ash	None	
Species	Stem Growth	
	Soil Variables	
Black pine	None	
Bayberry	None	
Norway spruce	None	
Ginkgo	None	
White pine	None	
Black gum	O ₂ , M.C.	
American basswood	None	
Hybrid poplar (rooted cuttings)	None	
Red maple	None	
Hybrid poplar (saplings)	None	
Sweet gum	None	
Sycamore	None	
Green ash	O ₂ , O ₂ *B.D.	
Pin oak	O ₂ *B.D.	
Japanese yew	O ₂ , M.C., O ₂ *B.D.	
Honey locust	None	

* Species are arranged in descending order from most tolerant of landfill conditions to least tolerant.

+ M.C.=moisture content, B.D.=bulk density, O₂=oxygen, O₂*B.D. = product of O₂ level and B.D. level, O₂*M.C.=product of O₂ level and M.C. level.

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Mean soil moisture content on the landfill and control plots from 1977 through 1979 is represented in Figure 7. Moisture content was consistently lower in the landfill plot than in the control. Soil moisture was maintained at adequate levels throughout 1979 by natural rainfall. Both plots were frequently irrigated during 1977 and 1978 in order to maintain moisture at levels high enough to prevent plant drought injury.

In order to investigate the effects of soil environment on tree growth a regression analysis was performed for shoot and stem growth for each of the 16 surviving species using soil O₂, moisture content (M.C.), bulk density (B.D.) and the interactions of O₂ with M.C. and O₂ with B.D. as independent variables (Table 19). The results of these analyses showed that soil parameters were more highly correlated with the intolerant species (those at the bottom of Table 19) than with the more tolerant species (those at the top of Table 19).

GAS-BARRIER EXPERIMENT

The following section reports on data collected from American basswood trees planted in the gas-barriers in 1976. Basswoods in the trench barrier areas were harvested in the spring of 1978 and replaced with seedlings of black gum, honey locust and pin oak.

Relative Viability of Plants

Six black gum, 5 pin oak and 3 honey locust trees died in the barrier trenches and on landfill and non-landfill unmodified areas during 1978 and 1979 (Table 20).

TABLE 20. NUMBER OF DEAD TREES IN LANDFILL AND CONTROL GAS-BARRIER TRENCHES AND IN UNMODIFIED LANDFILL AND CONTROL AREAS*

Area	Species			
	Black gum	Pin oak	Honey locust	Total
Control trench	1	1	1	3
Gravel/plastic/vents trench	1	1	0	2
Clay/vents trench	1	2	0	3
Clay trench	1	1	0	2
Unmodified landfill area	1	0	1	2
Unmodified control area	1	0	1	2
Total	6	5	3	14

* Six replicates of each species were originally planted in each area in Spring, 1978.

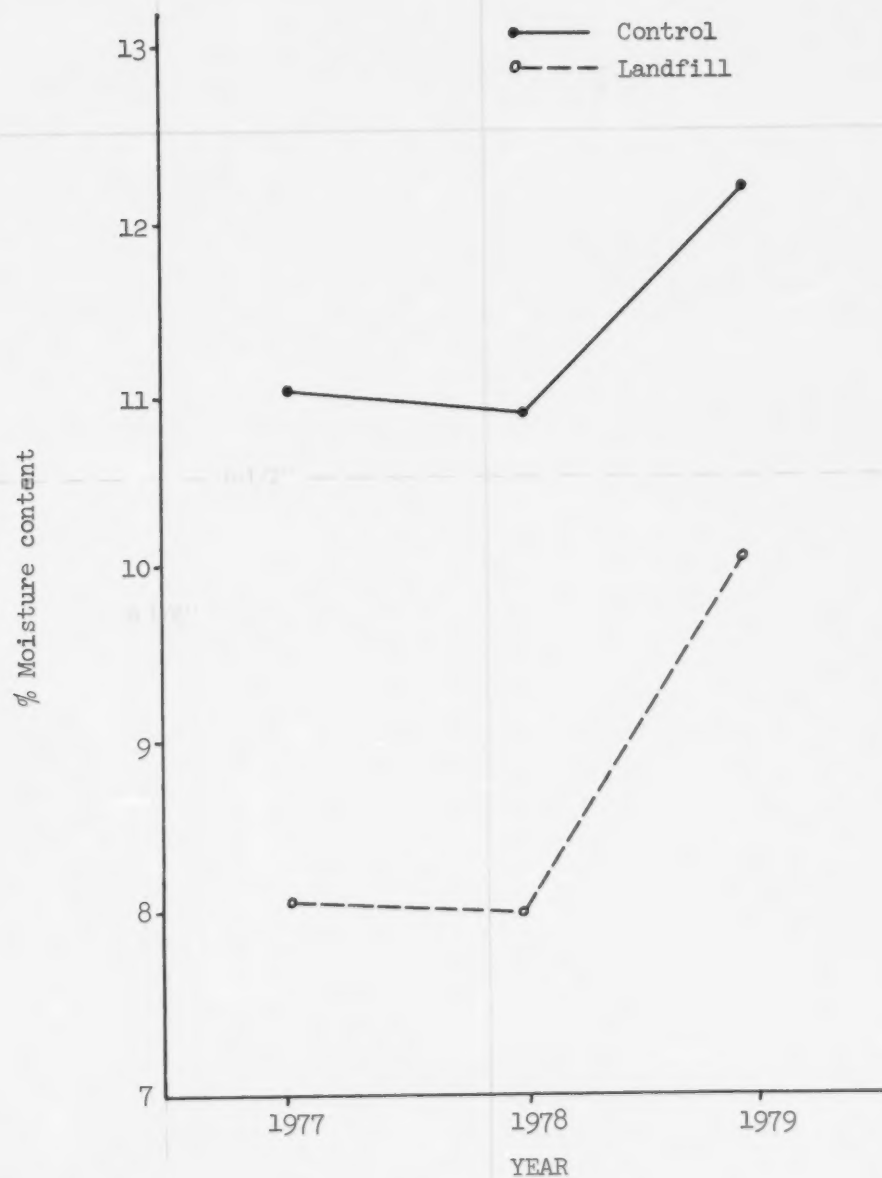
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Figure 7. Soil moisture content (% dry weight) in the top 20-cm of landfill and control soil during 1977, 1978 and 1979.

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Relative Growth of Surviving Plants

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In the surviving trees, black gum shoot growth was statistically similar in all six experimental areas during 1978; however, in 1979, shoot growth in the gravel/plastic/vents trench was significantly greater than in any other area (Table 21). Pin oak shoot growth was similar for all areas on the landfill plot. The differences between the control trench and unmodified control area and between clay trench and unmodified control area were significant at $P < .01$ during 1978. No significant differences were identified for pin oak shoot growth in 1979. Honey locust shoot growth during 1978 and 1979 was significantly greater ($P < .01$) in the gravel/plastic/vents trench than in all other areas.

Shoot and stem measurements were collected from American basswood and Japanese yew on the two landfill mounds, the control mound and on the unmodified landfill and control areas to determine if the growth of woody plants in mounded soil areas would be better than in unmounded areas (Table 22). American basswood growth was significantly improved in the landfill mound lined with a 30 cm (12 in) clay barrier over that in the unmodified landfill area during the first three years of the study period (1976-1978). During 1978, shoot and stem growth of yew in the clay-lined mound and stem growth in the unlined mound was significantly greater than in the unmodified landfill area but not in 1979.

Soil Variables

Soil CO_2 and CH_4 concentrations in the clay/vents trench were significantly higher and O_2 significantly lower than in the control trench (Table 23). Soil moisture in the three landfill trenches was significantly lower than in the control trench (Table 23).

The most striking nutrient difference among areas was the low available phosphorus, high NH_4 and high Fe in the clay/vents compared to the other three areas. Cu, Zn and Mn content were also highest in the clay/vents trench.

Basswood Growth Parameters

Measurements of four growth parameters for the nine gas-barrier areas during 1977 are shown in Table 24. Basswood root biomass, basal stem area increase and shoot length in the unmodified landfill area were significantly reduced compared to the unmodified control; however, there was no significant difference among areas for leaf weight. Basswood growth was also significantly reduced ($P < .01$) on the landfill mound and landfill clay mound compared to control mound for each of the four growth parameters. Root biomass in the three landfill trenches was not significantly reduced ($P < .01$) below that in the control trench; however, for the other three parameters, growth was less in the clay/vents trench, unchanged in the clay trench and significantly higher ($P < .01$) in the gravel/plastic/vents trench compared to the control trench.

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Growth on the landfill mounds and trenches was also compared with that

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TABLE 21. MEAN SHOOT LENGTH (cm) FOR TREES IN EACH GAS-BARRIER TRENCH AND UNMODIFIED AREA FOR 1978 AND 1979

Area	Species					
	Black gum		Pin oak		Honey locust	
	1978	1979	1978	1979	1978	1979
Control trench	12.0a	25.1a	9.8a	18.2a	30.9a	70.1a
Gravel/plastic/vents trench	9.2a	52.1b	13.6ab	20.8a	91.9b	135.9c
Clay/vents trench	10.3a	26.2a	13.3ab	24.3a	36.5a	73.1a
Clay trench	10.5a	28.9a	11.5a	19.0a	25.2a	83.6a
Unmodified control area	11.2a	22.3a	18.1b	25.6a	38.6a	118.4b
Unmodified landfill area	13.0a	23.5a	15.5ab	17.8a	---	70.6a

* Column means followed by different letters are significantly different from each other @ P<.01.
+ All shoots were destroyed by rabbits.

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TABLE 22. SHOOT LENGTH AND PERCENT STEM AREA INCREASE* FOR AMERICAN BASSWOOD AND JAPANESE YEW ON LANDFILL AND CONTROL MOUNDS AND UNMODIFIED AREAS DURING THE YEARS 1976 THROUGH 1979

Area	Species	1976			1977			1978			1979		
		Shoot Length (cm)	Stem Increase (%)		Shoot Length (cm)	Stem Increase (%)		Shoot Length (cm)	Stem Increase (%)		Shoot Length (cm)	Stem Increase (%)	
Unmodified Control	Jap. Yew	11.9	-		20.0	24.0		14.5	50.2		26.0	38.5	
	Basswood	19.8	-		17.2	50.0		8.4	27.2		23.7	64.5	
Unmodified Landfill	Jap. Yew	12.7	-		5.5	45.0		13.2	22.4		24.9	52.4	
	Basswood	18.9	-		9.7	26.8		9.1	26.4		18.7	78.9	
Control Mound	Jap. Yew	12.7	-		4.7	37.0		14.8	20.1		21.2	42.7	
	Basswood	19.0	-		17.0	30.0		26.1	32.1+		29.9	41.2	
Landfill Mound	Jap. Yew	17.5	-		4.7	14.0		17.2+	51.2		18.7	61.1	
	Basswood	27.9*	-		16.9	31.3		29.1+	29.1+		21.2	59.1	
Landfill Clay	Jap. Yew	18.0	-		7.0	26.2+		24.1+	41.6+		27.7	49.8	
	Basswood	30.9*	-		21.6	60.0		31.2	32.8		23.5	74.8	

* Stem measurements were not collected during 1976.

+ Significantly different from unmodified landfill area @ P<.01.

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TABLE 23. MEAN SOIL VARIABLE VALUES* IN EACH GAS-BARRIER TRENCH DURING 1978 AND 1979

Soil variable	Control trench		Gravel/plastic vents trench		Clay/vents trench		Clay trench	
	1978	1979	1978	1979	1978	1979	1978	1979
% O ₂	20.1a ⁺	20.0a	19.4b	19.2a	17.1b	17.1b	19.6a	18.21a
% CO ₂	1.2	1.0b	1.4b	1.9b	6.8a	5.4a	2.1b	1.9b
% CH ₄	0.0	0.0a	0.0a	0.0a	4.8c	2.4c	1.2b	0.8b
% Moisture content	10.1	12.1b	8.7a	9.2a	9.2a	10.1a	8.9a	10.0a
Conductivity	< 0.10	0.10	<	0.10	<	0.10	<	0.10
% Organic matter	3.2	3.1	2.6	2.9	3.1	3.0	2.7	3.1
pH	4.7	5.8	4.8	5.9	5.3	6.1	5.3	6.1
lbs/A								
Mg	51	6.2	50	49	59	60	97	98
P	121	141	115	118	15	75	223	191
K	122	121	155	124	83	98	110	121
Ca	205	891	134	610	223	841	178	716
NO ₃	17	16	13	15	9	12	4	17
NH ₄	19	19	8	12	48	50	12	21
ppm								
Fe	82	91	70	72	210	121	51	60
Cu	4.8	4.3	4.5	4.8	5.6	5.2	3.8	5.2
Zn	5.2	5.2	5.5	6.2	6.0	6.0	5.4	5.1
Mn	17.9	16.1	18.0	19.1	26.0	25.0	18.5	19.2
B	0.48	0.21	0.63	0.51	0.32	0.41	0.57	0.52

* Values are average of 20 readings collected at the 20 cm depth from late April thru mid-September.

+ Row means followed by different letters are significantly different at P<.01.

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TABLE 24. MEAN VALUES FOR AMERICAN BASSWOOD GROWTH PARAMETERS IN GAS-BARRIER AREAS DURING 1977

Area	Root biomass (mg)	Stem area (% increase)	Leaf weight (g)	Shoot length (cm)
Unmodified control	1865ab ⁺	50.0c	1.21b	18.6e
Unmodified landfill	572a	26.8b	1.01b	9.7b
Control mound	2838b	76.6d	6.7 e	34.5g
Landfill mound	622a	31.3b	1.9 c	16.9e
Landfill clay mound	930a	60.0c	3.4 d	21.6f
Control trench	1901ab	30.0b	2.0 c	13.3c
Landfill clay trench	1069a ⁺	23.9b	2.21c	14.2cd
Landfill clay/vents trench	153a ⁺	0.0a	0.02a	16.8a
Landfill gravel/plastic/ vents trench	800a	73.3d	4.0 d	22.8f

* % increase from March to September.

+ Column means followed by different letters are significantly different @ P<.01.

† Only one of the original six trees was alive at the end of 1977.

on the unmodified landfill area, thus allowing for an assessment of the ability of each of these five areas to promote better growth than the unmodified landfill. None of the trees in the five gas-barrier areas produced significantly more root biomass than in the unmodified landfill area. On the other hand, both the clay mound and gravel/plastic/vents trench produced significantly more stem area, leaf weight and shoot length than did the unmodified area. The landfill mound and clay trench produced greater leaf weight and shoot length, but similar stem area increase compared with the unmodified landfill area. Basswood growing in the clay/vents trench produced significantly less stem increase leaf weight or shoot length than in any other area.

Foliar Nutrient Uptake By American Basswood

American basswood leaf mineral content in the gas-barrier areas is given in Table 25. Mineral content of the foliage of trees from the unmodified landfill area for seven of the eight elements (nitrogen, potassium, magnesium, calcium, manganese, zinc and copper) was similar to that in the unmodified control area. Iron alone was significantly higher ($P < .05$) in content on the control plot. Nitrogen, calcium, manganese, zinc and copper contents did not differ significantly ($P < .05$) among the two landfill mounds and the control mound. However, the potassium content for trees was lower in the landfill mound and the iron content on the landfill mound and landfill-clay mound, higher than for trees on the control mound.

The most striking feature of the mineral content data was that American basswood foliage in the clay/vents trench contained significantly ($P < .05$) more magnesium and iron and significantly less nitrogen, potassium and manganese than did any other area including the control trench. The zinc concentration in the clay/vents trench did not differ significantly however, from those in any other trench. The nitrogen and potassium contents in the clay and gravel/plastic/vents trenches were significantly higher than in the control trench; however, no differences were detected for zinc and copper. Magnesium and calcium contents were lower for the clay trench and similar for the gravel/plastic/vents trench when compared to the control trench.

The increased ability of American basswoods growing in the landfill mounds and trenches to accumulate nutrients compared to unmodified conditions, can be assessed by comparing tissue element content in the trenches and mounds with contents in the unmodified landfill area (Table 25). The differences between the two landfill mounds and unmodified landfill area for potassium, calcium, zinc and copper were insignificant ($P < .05$) but the nitrogen content in both mounds was significantly greater than in the unmodified area. Although tissue magnesium content in the two mounds differed very little from that in the unmodified area, the clay mound contained significantly more magnesium than did the landfill mound and the unmodified area. American basswood contained a higher iron content in the landfill mound than in the unmodified area, but trees from the clay mound did not. The iron, zinc and copper contents in the clay and gravel/vents trenches did not significantly ($P < .05$) differ from those in the unmodified landfill area; however, nitrogen and potassium contents were increased significantly over the unmodified area in both trenches. Although the difference was very small, the magnesium content of American basswoods in the gravel/plastic/vents trench

TABLE 25. MINERAL ELEMENT CONTENT* OF AMERICAN BASSWOOD LEAF TISSUES IN GAS-BARRIER AREAS

Area	N %	K (X5000 ppm)	Mg (X5000 ppm)	Ca (X5000 ppm)	Mn (X500 ppm)	Fe (X200 ppm)	Zn (X500 ppm)	Cu (X200 ppm)
Unmodified control	3.13b ⁺	2.91c	0.91a	2.71c	5.91cd	6.48d	1.58a	0.71a
Unmodified landfill	3.17b	2.71bc	0.92a	2.79c	6.20cd	5.93bc	1.48a	0.77a
Control mound	3.61c	3.03cd	0.93a	2.95c	6.48d	4.63a	1.89a	0.76a
Landfill mound	3.51c	2.60b	0.95a	2.77c	6.65d	6.48d	1.84a	0.86ab
Landfill clay mound	3.98c	2.82bc	1.00b	2.85c	6.73d	5.93bc	1.65a	0.78a
Control trench	3.18b	2.52b	1.02b	2.52bc	3.62b	5.70b	1.23a	0.81ab
Landfill clay trench	3.96c	3.22d	0.89a	2.08a	3.42b	5.88bc	1.58a	0.76a
Landfill clay/vents trench	2.60a	2.13a	1.16c	1.77a	1.45a	7.60c	1.58a	0.89b
Landfill gravel/plastic vents trench	3.53c	3.37d	1.00b	2.48bc	5.95cd	6.20cd	1.14a	0.79a

* Each number is the mean of six replicate trees.

+ Column means with different letters are significantly different @ P<.05.

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was significantly greater than that of trees in the landfill unmodified area.

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Total mineral element uptake per branch was calculated for each tree and averaged for each experimental area (Table 26). The unmodified control area did not differ from the unmodified landfill screening area for any of the eight elements. In the landfill mound and landfill clay mound, American basswood accumulated less of every element than did trees on the control mound. The relative nutrient accumulation by American basswood among the four trenches was identical for each nutrient, i.e. the trees in the clay/vents trench accumulated less, those in the clay trench accumulated approximately the same and those in the gravel/plastic/vents trench accumulated more of each element than the control trench (Table 26).

Total accumulation per branch for each landfill barrier area was compared with the unmodified landfill area. The landfill mound and clay trench mineral element values did not differ significantly from the unmodified landfill screening area for any element except copper, which was significantly greater ($P < .05$) in these two areas than in the unmodified area. Trees in the landfill clay mound and gravel/plastic/vents trench accumulated significantly more of every element than did those in the unmodified area. On the other hand, total element uptake per branch for trees in the clay/vents trench was significantly lower than for those in the unmodified landfill area, except for copper which did not differ significantly ($P < .05$) from the screening area.

Soil Gas, Temperature, Moisture Content and Bulk Density Analyses

The soil oxygen and moisture contents on the unmodified landfill plot during 1977 were significantly reduced ($P < .01$) when compared to the control plot (Table 27). On the other hand, carbon dioxide, methane and soil temperature were significantly increased in the unmodified landfill plot. There was little difference in bulk density of two soils. The two landfill mounds did not differ from the control mound in any of the soil parameters except for soil moisture, which was significantly reduced on both landfill mounds.

The O_2 content was significantly lower and the CO_2 and CH_4 contents significantly higher in the clay trench and clay/vents trench than in the control trench. Soil temperature in the clay/vents and gravel trenches was significantly higher than in the control trench; whereas, bulk density was lower in the clay/vents and gravel/plastic/vents trenches. Soil bulk density in the clay trench was not significantly lower in the clay trench and gravel/plastic/vents trench compared to the control, however, moisture content in clay/vents trench was not significantly different from the control trench.

Soil Nutrient Analyses

The average nitrate (NO_3^-), ammonium (NH_4^+) nitrogen, potassium and manganese content in each area are given in Table 28 for samples collected on two separate dates in 1977. The $NO_3^-:NH_4^+$ ratios in June were relatively similar for all areas; however, by October, the $NO_3^-:NH_4^+$ ratio in the clay/vents trench was about half that in any other area either on the landfill or

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TABLE 26. TOTAL AMERICAN BASSWOOD UPTAKE OF MINERAL ELEMENTS PER BRANCH* IN NINE EXPERIMENTAL AREAS

Area	Mn (mg)	Fe (X400 ug)	K (X10 mg)	Mg (X10 mg)	Ca (X10 mg)	Zn (mg)	Cu (400 ug)	N (X100 mg)
Unmodified control	6.8b ⁺	7.5b	3.4b	1.1b	3.1b	1.8bcd	0.8a	3.6bc
Unmodified landfill	6.2b	5.9b	2.7b	0.9b	2.9b	1.5bc	0.7a	3.2bc
Control mound	45.6d	32.6e	21.3e	6.5e	20.8d	13.3f	5.4e	25.4f
Landfill mound	12.6b	12.3bc	4.9bc	1.8bc	5.3bc	3.5cde	1.6bc	6.6bcd
Landfill clay mound	22.9c	20.2cd	9.6cd	3.4cd	9.7c	5.6e	2.6cd	11.8de
Control trench	6.7b	10.5bc	4.7bc	2.0bc	6.0bc	2.2bcd	1.5bc	5.9bcd
Landfill clay trench	7.6b	12.8bc	7.1bc	2.0bc	4.6b	3.5cde	1.9bcd	7.6cd
Landfill clay/vents trench	0.3a	1.6a	0.4a	0.2a	0.4a	0.3a	0.2a	0.7a
Landfill gravel/plastic/vents trench	23.7c	24.6de	13.4de	3.9d	9.9c	4.5e	3.1d	14.0e

* Uptake per branch = Average weight of leaves per branch X mineral concentration (ppm).

+ Column means with different letters are significantly different @ P<.05.

TABLE 27. LEVELS* OF SOIL GASES, TEMPERATURE, SOIL MOISTURE AND BULK DENSITY⁺
IN THE GAS-BARRIER AREAS DURING 1977

Area	O ₂ (%)	CO ₂ (%)	CH ₄ (%)	Temperature (°F)	Soil moisture (% dry wt.)	Bulk density (g/cc)
Unmodified control	19.7d [#]	1.2a	0.0a	64.3a	11.0d	1.82b
Unmodified landfill	17.8c	5.5b	0.9b	66.3b	8.1b	1.85b
Control mound	19.4d	1.2a	0.0a	64.1a	10.7d	1.45a
Landfill mound	20.3d	0.8a	0.0a	64.3a	7.3a	1.33a
Landfill clay mound	20.3d	0.8a	0.0a	64.3a	7.5a	1.44a
Control trench	19.6d	1.2a	0.0a	63.2a	10.5d	1.72b
Landfill clay trench	16.3b	7.0b	0.7b	65.2ab	8.4b	1.67b
Landfill clay/vents trench	4.3a	22.8c	11.8c	70.7c	11.0d	1.41a
Landfill gravel/ plastic/vents trench	19.8d	1.3a	0.0a	70.1c	9.0c	1.29a

* Each value is the average of 30 individual measurements.

+ Bulk density was measured once in mid-summer at the same points gas samples were collected.

Column means followed by different letters are significantly different @ P<.01.

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TABLE 28. LEVELS OF SELECTED NUTRIENTS* IN EACH OF THE GAS-BARRIER AREAS (1977)

	NO ₃ (ppm)		NH ₄ (ppm)		NO ₃ :NH ₄ ⁺ Ratio		K (ppm)		Mn (ppm)	
	June	Oct.	June	Oct.	June	Oct.	June	Oct.	June	Oct.
Control	52	29	262	11	0.20	2.6	173	104	85	21
Landfill	33	14	185	5	0.18	2.8	178	69	41	6
Control mound	67	42	280	11	0.24	3.8	200+	102	77.5	14
Landfill mound	28	7	290	2	0.10	3.5	200+	92	50	8.5
Landfill clay mound	23	20	170	8	0.14	2.2	177	119	72.5	11
Control trench	31	15	180	3	0.17	5.0	192	95	44	12.5
Landfill clay trench	25	6	140	2	0.18	3.0	192	84	50	6
Landfill clay/vents trench	30	6	198	6	0.15	1.0	168	62	55	45
Landfill gravel/plastic/vents trench	60	10	310	4	0.19	2.5	200+	80	90	6.5

* Since each nutrient was measured once in each area on each date, statistical analysis was not possible.

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control plot. There were no other discernable soil nutrient trends other than a small decrease from June to October in the manganese concentration of the clay/vents trench compared to a relatively large decrease in all other areas, resulting in a high manganese (45 ppm) concentration by October in the clay/vents trench (Table 28).

Soil bulk density and root biomass were both correlated with tree nutrient uptake in the nine barrier areas (Table 29). Since root biomass is apparently influenced by landfill soil conditions and root biomass is positively correlated with total nutrient uptake, then the efficiency with which the root system accumulates nutrients may be assessed by analyzing total nutrient uptake differences between areas after removing the linear effect of root biomass on nutrient uptake. If the effects of bulk density and root biomass on nutrient uptake are removed by analysis of covariance, the efficiency of nutrient accumulation can be evaluated since the linear relationship of root biomass and bulk density with nutrient accumulation/branch is removed. After adjusting the eight nutrient means in each area for these two effects (Table 30), nutrient accumulation in the gravel/plastic/vents trench and clay mound was no longer significantly greater than that in the experimental screening area as it was with the unadjusted means (Table 28). Therefore, basswoods in four of the five gas-barrier areas (both mounds, gravel trench, clay trench) have accumulated eight nutrient elements as efficiently as those in the unmodified landfill and unmodified control areas (Table 30). However, nutrient accumulation efficiency was severely reduced in the clay/vents trench where the landfill gas concentration was significantly greater than in any of the above areas (Table 30).

TABLE 29. CORRELATION COEFFICIENTS OF ROOT BIOMASS AND SOIL BULK DENSITY WITH TOTAL NUTRIENT UPTAKE FOR EIGHT NUTRIENTS IN AMERICAN BASSWOOD LEAF TISSUE

Tissue nutrient	Root biomass	Bulk density
Mn	0.64 ⁺	-0.46 ⁺
Fe	0.59 ⁺	-0.44 ⁺
K	0.66 ⁺	-0.46 ⁺
Mg	0.70 ⁺	-0.44 ⁺
Ca	0.72 ⁺	-0.47 ⁺
Zn	0.75 ⁺	-0.51 ⁺
Cu	0.69 ⁺	-0.49 ⁺
N	0.69 ⁺	-0.44 ⁺

⁺ Significant @ P<.01.

⁺ Significant @ P<.05.

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TABLE 30. AMERICAN BASSWOOD ELEMENT UPTAKE PER BRANCH* FOR EIGHT NUTRIENTS IN NINE EXPERIMENTAL AREAS
ADJUSTED FOR BULK DENSITY AND ROOT BIOMASS

Area	Nutrient							
	Mn (mg)	Fe (x400 ug)	K (x10 mg)	Mg (x10 mg)	Ca (x10 mg)	Zn (mg)	Cu (x400 mg)	N (x100 mg)
Unmodified landfill	17.5b	16.7cb	8.3b	2.6bc	8.1b	4.6b	2.4b	9.5b
Unmodified control	14.7b	1.51cb	7.2b	2.2bc	6.7b	3.9b	2.0b	7.9b
Gravel/plastic vents trench	14.6b	15.9cb	8.9b	2.6bc	5.7b	2.1b	1.8b	9.1b
Clay/vents trench	3.3a	0.1a	1.3a	0.3a	1.2a	0.6a	0.3a	1.2a
Clay trench	11.5b	16.6cb	9.0b	2.6bc	6.4b	4.6b	2.5b	9.8b
No-clay mound	10.3b	5.3b	4.4b	2.1ab	2.0b	1.6b	0.6ab	2.7b
Clay mound	19.1b	16.6cb	7.7b	2.8c	8.0b	4.6b	2.1b	9.8b
Control mound	38.6c	26.2c	17.8c	5.4d	17.5c	11.3c	4.5c	21.3c
Control trench	11.8b	15.5cb	7.2b	2.8c	7.4b	3.6b	2.2b	8.7b

* Column means followed by different letters are significantly different from one another at $P < 0.01$.

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EFFECT OF PLANTING STOCK SIZE ON SPECIES ADAPTABILITY TO LANDFILLS

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In order to evaluate the effect of original size of woody vegetation at the time of planting on landfill tolerance, shoot growth on small (1-2' (30-60 cm) tall) and large (6-10' (180-300 cm) tall) replicates of five species was measured on trees in the landfill and control plots (Table 31). Shoot growth of small pin oak, green ash, sugar maple and hybrid poplar (rooted cuttings) was not statistically lower on the landfill plot than on the control. Conversely, shoot growth of the large replicates of these same four species was significantly less on the landfill than in the control plot. This relationship was reversed for one species, honey locust. The large replicates exhibited no shoot growth difference between plots; whereas, shoot growth of the small trees was significantly lower on the landfill than on the control.

TABLE 31. TOTAL SHOOT GROWTH* OF SMALL+ AND LARGE PIN OAK, GREEN ASH HONEY LOCUST, SUGAR MAPLE AND HYBRID POPLAR ON LANDFILL AND CONTROL PLOTS DURING 1978 AND 1979

Species	Size	Landfill (cm)	Control (cm)	Landfill as % control	Significance level#
Pin oak	Small	33.3	43.7	76.2	N.S.
	Large	52.0	82.5	63.0	.08
Green ash	Small	64.6	95.2	67.8	N.S.
	Large	44.3	100.1	44.2	.01
Honey locust	Small	70.6	157.0	45.0	.01
	Large	119.4	146.6	81.4	N.S.
Sugar maple	Small	23.8	34.8	68.4	N.S.
	Large	15.7	34.5	45.5	.05
Hybrid poplar	Small	203.5	219.2	92.8	N.S.
	Large	83.3	210.7	39.5	.01

* Total shoot growth=shoot growth during 1978 plus shoot growth during 1979.

+ Six small-sized trees and ten large sized trees of each species were originally planted on each plot.

Comparing landfill plot mean with control plot mean. N.S.=not significant @ P<.10, number indicate significance level.

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EFFECT OF BALLED AND BURLAPPED VS. BARE-ROOT CONDITION ON GROWTH OF SUGAR MAPLES

Shoot growth of balled and burlapped sugar maples on the landfill plot was similar to growth on the control plot; however, growth of bare-rooted trees was significantly lower ($P < .05$) on the landfill than on the control plot (Table 32). In addition, shoot growth of the balled and burlapped maples on the landfill plot was significantly greater than that of the bare-rooted maples; whereas, growth of the two types of trees was statistically similar on the control.

TABLE 32. MEAN SHOOT LENGTH* FOR BALLED AND BURLAPPED AND BARE-ROOTED SUGAR MAPLES ON LANDFILL AND CONTROL PLOTS

Root Treatment	Landfill		Control		Landfill as % control [†] (%)
	1978	1979	1978	1979	
Balled and burlapped	9.2	22.3	8.2	22.1	104 N.S.
Bare-rooted	4.9	10.8	10.1	22.4	46

* Each value is the mean for six shoots measured on each of five trees.

+ Percentage was calculated from the total shoot length computed as 1978 growth plus 1979 growth.

† Differences significant at $P < .01$.

EFFECTS OF IRRIGATION ON SUGAR MAPLE GROWTH

Soil Parameters

Carbon dioxide concentrations (Table 33) were significantly higher ($P < .01$) in the landfill plot (2.1% to 8.1%) than in the control (1.2% to 1.8%) during the 1978 and 1979 growing seasons. Oxygen concentrations varied from 15.8% to 18.1% in the landfill plot and from 19.2% to 20.1% in the control, resulting in a significantly lower oxygen content in the landfill (mean from irrigated and non-irrigated areas) (17.0%) than in the control (mean from irrigated and non-irrigated areas) (19.8%). Methane was not detected in either of the plots.

Gas readings in the irrigated and non-irrigated control areas and landfill irrigated area were alike within each treatment area throughout the summer. However, within the landfill non-irrigated area, the carbon dioxide readings were consistently higher and oxygen consistently lower in the southern sampling point than in the northern gas sampling station.

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TABLE 33. AVERAGE CARBON DIOXIDE AND OXYGEN CONCENTRATIONS IN
LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Gas	Year	Landfill		%	Control	
			North	South		North	South
Irrigated	O ₂	1978	17.8	17.9		19.7	19.8
		1979	18.1	17.9		20.1	20.0
		Mean	17.9			19.9	
	CO ₂	1978	2.4	2.1		1.4	1.7
		1979	3.4	2.4		1.2	1.5
		Mean	2.6			1.4	
Non-Irrigated	O ₂	1978	16.9	15.8		19.8	19.2
		1979	16.4	15.8		20.1	19.9
		Mean	16.2			19.7	
	CO ₂	1978	2.8	7.8		1.8	1.3
		1979	3.4	8.1		1.3	1.4
		Mean	5.5			1.4	

* Each average was calculated from 12 readings at 20 cm (2-8 in) deep sampling locations totaling 24 readings.

Soil temperatures during the summers of 1978 and 1979 were statistically higher ($P < .01$) on the landfill irrigated (19.8°C (66.7°F)) and landfill non-irrigated (19.4°C (66.9°F)) plots than in the control (18.2°C (64.7°F)) but there were no other differences (Table 34).

Soil moisture was significantly lower than in the control plot (Table 35) throughout both summers. Irrigating the landfill and control areas significantly increased soil moisture compared to the non-irrigated areas during 1978, but not during 1979. The increase was similar for both the landfill and control plots.

Soil nutrient levels in each of the four areas (Table 36) were similar for most elements except that in the control irrigated plot the calcium was considerably lower and the iron was much higher than in the other three treatment areas. The magnesium content in the control non-irrigated area was also much higher than in the other three areas.

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TABLE 34. AVERAGE SOIL TEMPERATURES* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Year	Landfill		Control	
		North	South	North	South
Irrigated	1978	19.5	19.3	18.2	18.4
	1979 ⁺	(67.1)	(66.8)	(64.8)	(65.1)
	Mean	19.0	19.3	18.4	17.9
Non-Irrigated	1978	19.8	(66.7) [†]	18.2	(64.8)
	1979 ⁺	(66.2)	(66.8)	(65.1)	(64.2)
	Mean	19.1	19.5	18.3	(64.9)
	1978	18.9	(67.1)	18.4	(65.1)
	1979 ⁺	(66.1)	(67.9)	(65.2)	(64.7)
	Mean	19.4	(66.9) [†]	18.2	(64.7)

* Each average was calculated from 12 readings at 20 cm (2-8 in) deep sampling locations totaling 24 readings.

+ Mean computed from 96 readings.

† Significantly greater than control plot @ P<.01.

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TABLE 35. SOIL MOISTURE* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill		Control	
	1978	1979	1978	1979
Irrigated	9.4b ⁺	10.1bc	11.1cd	12.0d
Non-Irrigated	7.1a	9.3b	9.8b	11.1cd
Mean	8.3	9.7	10.5	11.5

* Soil moisture on a % dry weight basis. Each value was computed from 12 moisture readings at 3 samples locations totaling 36 readings.

+ Numbers followed by different letters are significantly different from each other @ P<.01.

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TABLE 36. SOIL NUTRIENT VALUES* IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS IN OCTOBER 1978

	Landfill		Control	
	Irrigated	Non-Irrigated	Irrigated	Non-Irrigated
	(ppm)			
Nitrate	8	9	18	9
Nitrogen				
Ammonium	12	12	16	12
Nitrogen				
Phosphorus	31	19	17	12
Potassium	83	35	65	118
Magnesium	26	30	20	95
Calcium	134	267	62	267
Boron	0.63	0.58	0.50	0.47
Copper	6.5	2.5	4.5	3.5
Manganese	30.0	18.0	23.0	44.0
Iron	81.0	55.0	300.0	51.0
Zinc	10.0	3.5	3.6	6.5
Texture	Sandy Loam	Sandy	Sandy	Sandy Loam/
	Loamy Sand	Loam	Loam	Sandy Clay Loam

* Values are the mean from 2 samples taken from each plot on one sampling day in October 1978.

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Shoot growth of sugar maples on the control was significantly greater than on the landfill plot during 1978 and 1979 (Table 37). Growth was reduced on the non-irrigated areas of both plots, this difference was statistically significant only on the landfill in 1979. Despite the nonsignificance during 1978, the average absolute reduction in shoot growth in non-irrigated vs. irrigated areas on the landfill plot was more than twice that on the control.

TABLE 37. MEAN SHOOT LENGTH* OF SUGAR MAPLES⁺ IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill		Control	
	1978	1979	1978	1979
Irrigated	10.2a ^Δ	20.1d	12.8b	24.6e
Non-Irrigated	9.0a	15.4c	12.4b	23.2e

* Each value was computed from measurements on 30 trees.

+ Thirty 2-year old seedling were originally planted in each of 4 areas: landfill and control irrigated and non-irrigated areas.

Δ Values followed by different letters are significantly different at $P < .01$.

Sugar maples growing on the landfill plot produced significantly ($P < .01$) fewer nodes and, therefore, fewer leaves/shoot than those on the control plot (Table 38). Irrigating did not significantly increase the number of leaves/shoot on either plot.

TABLE 38. NUMBER OF NODES PER SHOOT ON SUGAR MAPLES IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill plot		Control plot	
	1978	1979	1978	1979
Irrigated	3.22ab*	3.31b	3.32b	4.89c
Non-Irrigated	2.89a	3.35b	3.46b	4.72c
Mean	3.1	3.3	3.4	4.8
	3.2		4.10 [†]	

* Values followed by different letters are statistically different @ $P < .01$.

† Significantly greater than landfill plot @ $P < .06$.

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Average leaf dry weight sugar maples was significantly less ($P < .01$) in the landfill plot than the control plot (Table 39). In addition, irrigating the landfill plot significantly increased leaf weight; whereas on the control, no significant difference was shown between the irrigated and non-irrigated areas.

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TABLE 39. AVERAGE DRY WEIGHT* OF SUGAR MAPLE LEAVES IN LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS

Area	Landfill		Control	
	1978	1979	1978	1979
Irrigated	0.66b ⁺	0.72b	0.83c	0.86c
Non-Irrigated	0.50a	0.55a	0.86c	0.87c
Mean	0.58	0.63	0.84	0.86
	0.61		0.85 [†]	

* Values were average for 2 leaves/tree from 30 trees/plot treatment/year.

+ Values followed by different letters are significantly different from each other @ $P < .01$.

Significantly greater than landfill plot @ $P < .01$.

Stomatal Resistance

Diffusive resistance readings were made on sugar maple leaves in the irrigated and non-irrigated landfill areas in order to evaluate the effect of soil moisture content on stomatal strategies of trees growing on landfills. Resistance measured every hour during August 18, 1978 on maples growing on the landfill plot in the irrigated area and high and low landfill gas non-irrigated areas decreased significantly and similarly between 8:30 a.m. and 10:30 a.m. (Figure 8). By 11:30 a.m. leaf resistance of trees in the high-gas (south) non-irrigated area increased sharply to the 8:30 a.m. level and fluctuated around this level for the remainder of the day. Diffusive resistance readings of leaves in the low-gas (north) non-irrigated area tended to hover close to the 11:30 a.m. reading (except for a peak at 2:30 p.m.) until the day's end when readings were close to the original early morning level. Unlike readings for the aforementioned areas, readings in the low-gas irrigated area (Figure 8) continued to decrease until 12:30 p.m. when resistance was lowest, then gradually increased through 4:30 p.m. after which resistance increased sharply. Readings for the high-gas (south) non-irrigated area were significantly higher than for the other two areas from 11:30 a.m. through 5:30 p.m. Only two points differed significantly between low-gas irrigated and low gas non-irrigated i.e. at 2:30 p.m. and 6:30 p.m. (Figure 8).

During the period from August 9 through August 23, 1978, diffusive resistance readings for sugar maple leaves were significantly increased on the landfill plot compared to the control plot (Table 40). Resistance on the

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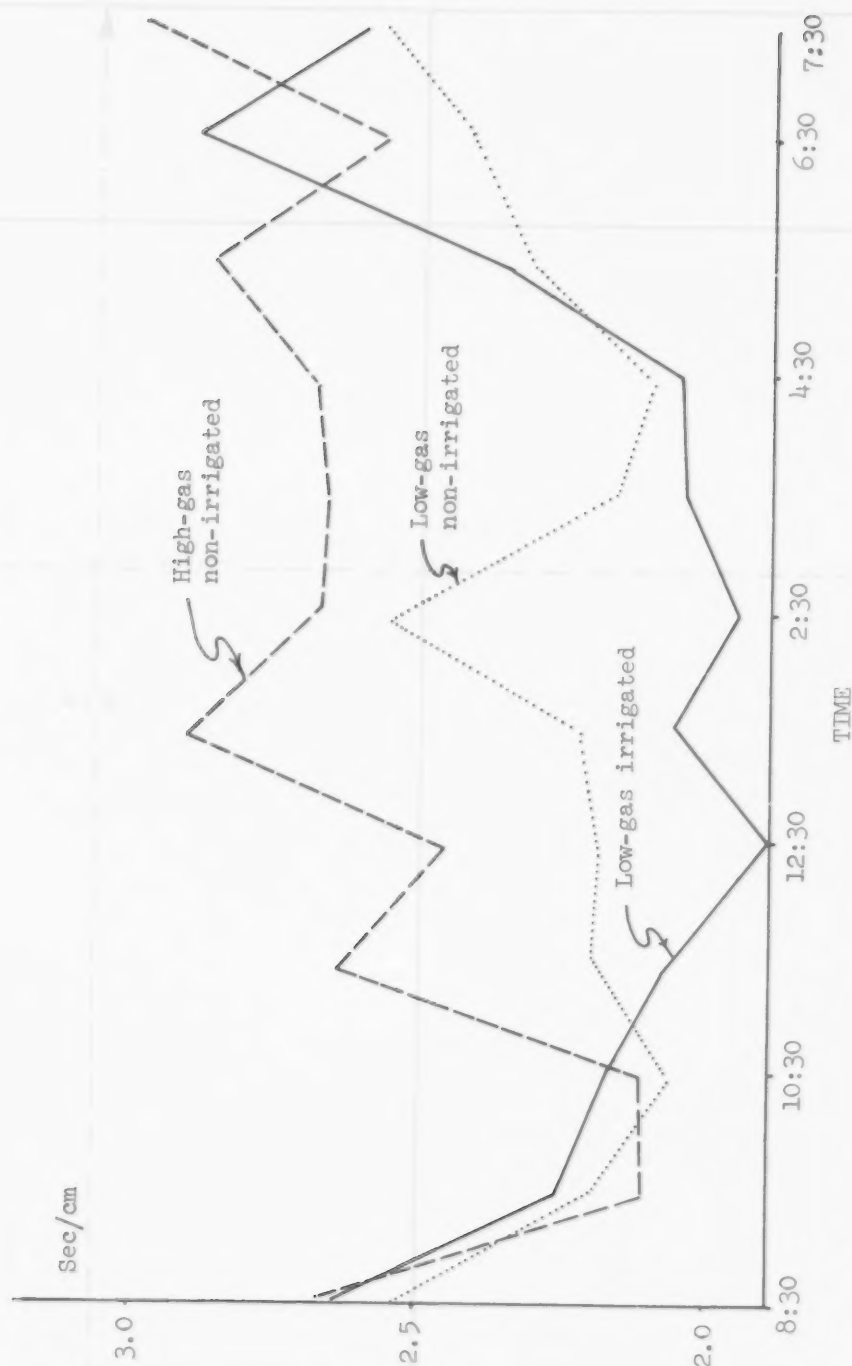


Figure 8. Stomatal resistance for sugar maples on August 18, 1978 for irrigated and non-irrigated landfill areas.

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non-irrigated areas was significantly greater than the increase on the control.

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TABLE 40. DIFFUSIVE RESISTANCE READINGS* FOR SUGAR MAPLE ON LANDFILL AND CONTROL IRRIGATED AND NON-IRRIGATED AREAS FROM AUGUST 9 THROUGH AUGUST 23, 1978

Area	Landfill	Control
	----- sec/cm -----	
Irrigated	2.2a ⁺	2.2a
Non-Irrigated	2.7b	2.3a
Mean	2.45 [‡]	2.25

* Readings are average of 2 readings/tree for 5 trees in each area. Readings were taken between 10:00 a.m. and 12:00 a.m. each day.

+ Values followed by different letters are significantly different @ P<.05.

‡ Significantly greater than control plot @ P<.01.

Effects of Soil and Meteorological Parameters on Stomatal Resistance

When air temperature and relative humidity during August 18 were regressed onto diffusive resistance readings for maples in the high-gas (south) non-irrigated area (CO₂=7.8%, O₂=15.8%), no effects were statistically significant even at the P<.50 level, to justify a descriptive multiple regression model. However, in the low-gas non-irrigated area (CO₂=2.8%, O₂=16.0%) 16% of the variability of diffusive resistance readings could be accounted for in the model:

$$D = 80.4 - 13.1 \log_N(T_A). \quad \text{eq 1, } R^2 = 16\%$$

where:

D = Diffusive Resistance

T_A = Air Temperature, °F

Log_N = Natural Logarithm

While this model did not account for much of the variability in diffusive resistance readings, the model describing variability in readings for the low-gas irrigated area (CO₂=2.3%, O₂=17.9%):

$$D = 1271.0 - 21.3 (T_A) + 0.1 (T_A)^2 - 131.5 \log_{10} (R) \quad \text{eq 2}$$

where:

D = Diffusive Resistance

T_A = Air Temperature, °F

R = % Relative Humidity

accounted for 71% of the variability.

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Regression of the independent variables: soil gas, soil moisture and meteorological data from August 9 through August 23 onto diffusive resistance of sugar maple leaves was performed for the irrigated and non-irrigated areas on both plots. Variation of resistance readings from day to day in both the control irrigated and non-irrigated areas was correlated with changes in total wind movement from day to day according to the models:

For control irrigated

$$D = 12.4 + \frac{222.8}{\text{wind}} \quad R^2=43\%, P<.05 \quad \text{eq 3}$$

where:

D = Diffusive Resistance

For control non-irrigated

$$D = 14.6 + \frac{211.8}{\text{wind}} \quad R^2=53\%, P<.01 \quad \text{eq 4}$$

where:

D = Diffusive Resistance

When untransformed linear values of the independent variables were used in the regression on the landfill plot, air temperature was positively correlated with resistance readings on the irrigated area ($R^2=19\%$), whereas, oxygen was negatively correlated ($R^2=62\%$) with readings on the non-irrigated area where the oxygen content varied significantly more than in all other areas.

When reciprocal and quadratic effects were added to the regression, resistance readings for maples on the landfill plot were correlated with moisture content and oxygen:

For experimental irrigated

$$D = 32.4 + 0.9 (\text{M.C.})^2 - 3.1 (\text{M.C.})^{3/2} \quad R^2 = 64\% \quad P<.03$$

For experimental non-irrigated

$$D = -13.0 + 474.1/O_2 \quad R^2=72\% \quad P<.01$$

where:

D = Diffusive Resistance

M.C. = Moisture Content

O₂ = Oxygen concentration

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EFFECTS OF THE SOIL ENVIRONMENT IN SIX TREATMENT AREAS ON ROOT DISTRIBUTION OF AMERICAN BASSWOOD

In the clay/vents trench where the CO₂, O₂ and CH₄ concentrations averaged 22.8%, 4.3% and 12.0% respectively (Table 41) throughout the 1977 growing season, total root length averages 241 cm. Conversely, in the gravel/plastic/vents trench, the CO₂ concentration averaged 1.4%; O₂, 19.8%; CH₄, 0.1%, and total root length was 1676 cm. The concentration of landfill gas (CO₂ and CH₄) present in the soil atmospheres was negatively correlated (r=0.69 and -0.52 respectively), whereas oxygen was positively correlated (r=+0.72) with total root length. Multiple regression analysis of total root length produced the following equation: Total Root Length (cm) = 3132.3 - 110.3 CO₂ + 112.9 O₂ with an R² = 84%.

TABLE 41. ROOT LENGTH, AVERAGE AND MAXIMUM DEPTH, AND FREQUENCY OF ROOT GROWTH DIRECTION CLASS FOR AMERICAN BASSWOOD; *SOIL CARBON DIOXIDE, METHANE AND OXYGEN CONCENTRATIONS⁺ IN EACH AREA

Parameter	Trench area					
	Unmodified landfill area	Unmodified control area	Gravel plastic vents trench	Clay vents trench	Clay trench	Control trench
Total root length (cm)	789b ^Δ	2204c	1676c	241a	1922c	1762c
Average root depth (cm)	7.4a	20.8b	24.4b	18.0b	18.3b	18.8c
Maximum root depth (cm)	15.1a	71.1b	81.3b	20.3a	60.9b	81.3b
% Of total root length which grew downward	9.5	46.8	51.6	0.0	32.4	53.0
% Of total root length which grew up toward soil surface	66.7	38.9	35.5	68.3	59.5	41.7
% Of total root length which grew parallel to soil surface	23.8	14.3	12.9	31.7	8.1	5.3
% O ₂	18.5a	19.5a	19.8a	4.3b	17.2c	19.6a
% CO ₂	8.1b	1.0a	1.4a	22.8c	5.8b	1.2a
% CH ₄	0.9 b	0.0a	0.1a	12.0c	0.1a	0.0a

* Each value is the mean for two trees.

+ Each value is the mean of 12 readings at 30 cm soil depth throughout the growing season. Concentrations are in % by volume.

Δ Values followed by different letters are significantly different at P<.05.

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Average root depth in each area is presented in Table 41. Roots in the unmodified landfill area had a significantly shallower depth than in all other areas. The maximum depth of root penetration in the clay/vents trench and unmodified landfill areas was a third of that in other areas. Results of Chi-Square Analysis showed that there was a significant relationship between distribution of root growth and the six trench areas (Table 41). Subdividing the Chi-Square Analysis shows that the distribution of roots in the root growth-direction classes in the unmodified landfill area and the clay/vents trench, was significantly different from that in the remaining four areas. In these two areas, the CO_2 and CH_4 concentrations were considerably higher in all other treatments.

The frequency distribution differences among areas were particularly pronounced in the "percentage downward root growth" row of Table 41 where the trees in the unmodified landfill and clay/vents trench areas locate 9.5 or 0% of their roots, respectively, compared to 32.4% or more for all other treatments. There appear to be two treatment groups in the "percentage upward root growth" row: one consisting of unmodified landfill area, clay/vents trench, and clay trench where the soil CO_2 content ranged from 5.8 to 22.8%; and another consisting of unmodified control area, gravel/plastic/vents trench and control trench where the soil CO_2 content ranged from 1.0 to 1.4%. In the first group (high CO_2) 59.5% or more of the roots grew toward the soil surface, whereas, fewer than 41.7% grew upward in the latter group (low CO_2).

Chi-Square Analysis of root depth class versus treatment area indicated a dependency between the frequency of roots in each depth class and the six treatment areas (Table 42). Upon subdividing the analysis, the frequency distribution in the unmodified landfill area and clay/vents trench was found to be different than in all other areas i.e. all roots were growing in the top 23 cm of soil in these two treatment areas. On the other hand, in all other areas, some roots penetrated at least to 46 cm below the soil surface. The frequency distributions of roots in the gravel/plastic/vents trench, clay trench, control trench, and unmodified control areas were not significantly different ($P < .05$) from each other.

EFFECTS OF LANDFILL SOIL ENVIRONMENT ON ROOT DISTRIBUTION OF FIVE WOODY SPECIES

Mean root depth and total root length (roots with diameter of 1 mm or more) for five species on the landfill and control plots are presented in Table 43. Mean root depth for Japanese black pine, and hybrid poplar saplings and rooted cuttings, honey locust and green ash saplings was less on the landfill plot than on the control plot. Norway spruce was the only species with a root system that was deeper on the landfill plot than on the control. Root length for Norway spruce and Japanese black pine was also slightly greater on the landfill than on the control area. Root length for the remaining three species was less on the landfill than on the control (Table 43).

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The percentage of roots at each soil depth is given in Figures 9 through 15 for the five species excavated for extensive root study. In root depth classes of 10.1 cm or greater, the bar represents the average percentage for

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TABLE 42. PERCENTAGE OF ROOTS IN EACH ROOT-DEPTH CLASS FOR EACH TRENCH AREA

Root- depth class (cm)	Unmodified landfill area	Unmodified control area	Trench Area			Control trench
			Gravel plastic vents trench	Clay vents trench	Clay trench	
0- 8.0	71.4a†	23.8c	25.8c	0.0b	24.3c	19.2c
> 8.0-15.0	28.6	25.7	22.5	33.3	24.3	27.2
> 15.0-23.0	0.0	20.7	6.5	66.7	21.6	24.9
> 23.0-30.0	0.0	14.8	9.7	0.0	13.5	17.9
> 30.0-38.0	0.0	3.9	3.2	0.0	5.4	5.4
> 38.0-45.0	0.0	5.6	12.9	0.0	5.4	2.7
> 45.0-53.0	0.0	5.5	16.1	0.0	5.4	2.7
below 53.1	0.0	0.0	3.3	0.0	0.0	0.0

† Columns with similar letters have similar distribution by Chi-square analysis @ P < .05.

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TABLE 43. MEAN ROOT DEPTH* AND TOTAL ROOT LENGTH* FOR SEVERAL SPECIES ON LANDFILL AND CONTROL PLOTS

Species	Landfill		Control		Landfill as % of control	
	Depth (cm)	Length (m)	Depth (cm)	Length (m)	Depth (cm)	Length (m)
Japanese black pine	7.8	25.4	9.3	23.0	83.9	106.5
Norway spruce	5.1	28.6	4.2	26.2	121.4	109.2
Hybrid poplar (rooted cuttings)	6.3	90.8	13.6	113.5	46.3	80.0
Honey locust	8.3	16.9	16.6	53.0	50.0	31.9
Green ash (saplings)	9.3	44.9	14.7	94.3	63.4	47.6
Hybrid poplar (saplings)	8.5	35.9	12.8	97.5	66.4	36.8

* Each value is the mean of 2 replicates.

+ Species are arranged from most to least tolerant of landfill conditions according to Table 12.

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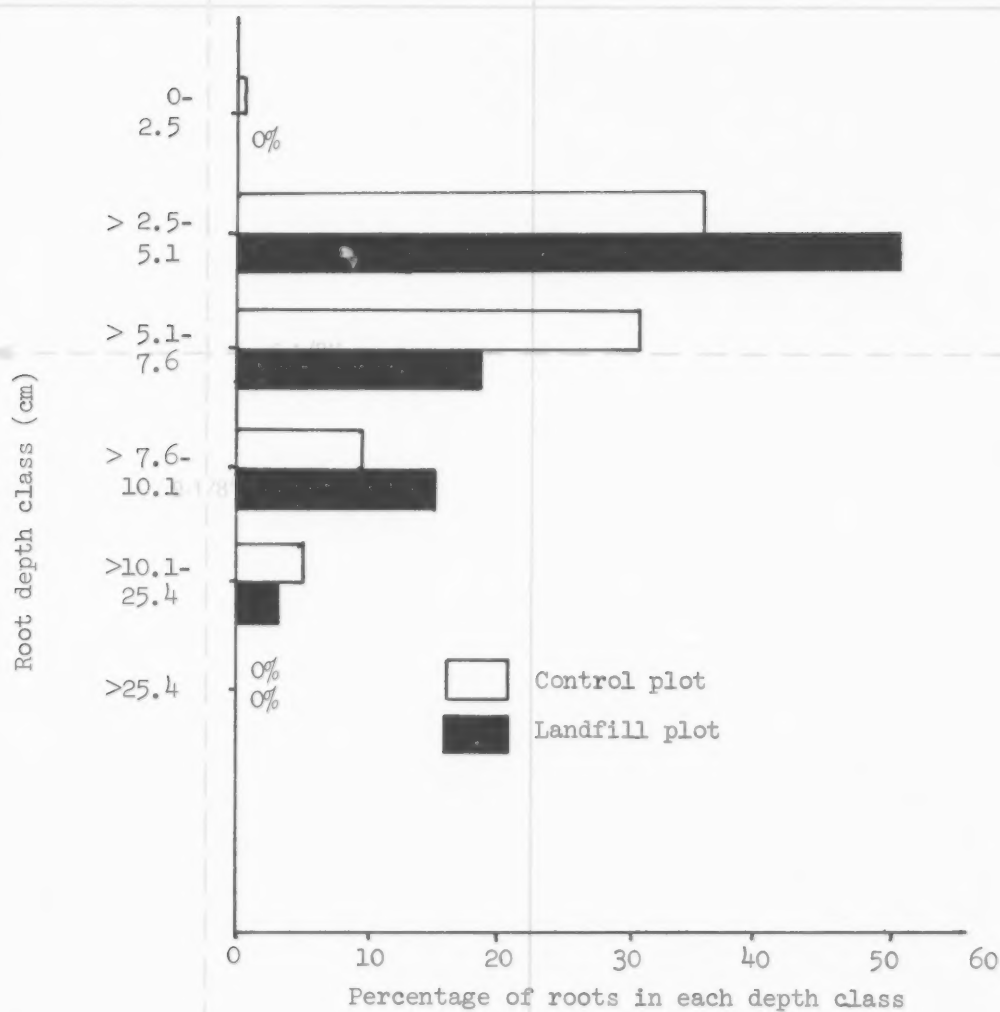


Figure 9. Vertical root distribution of Japanese black pine in landfill and control plots. Each is the mean for two trees.

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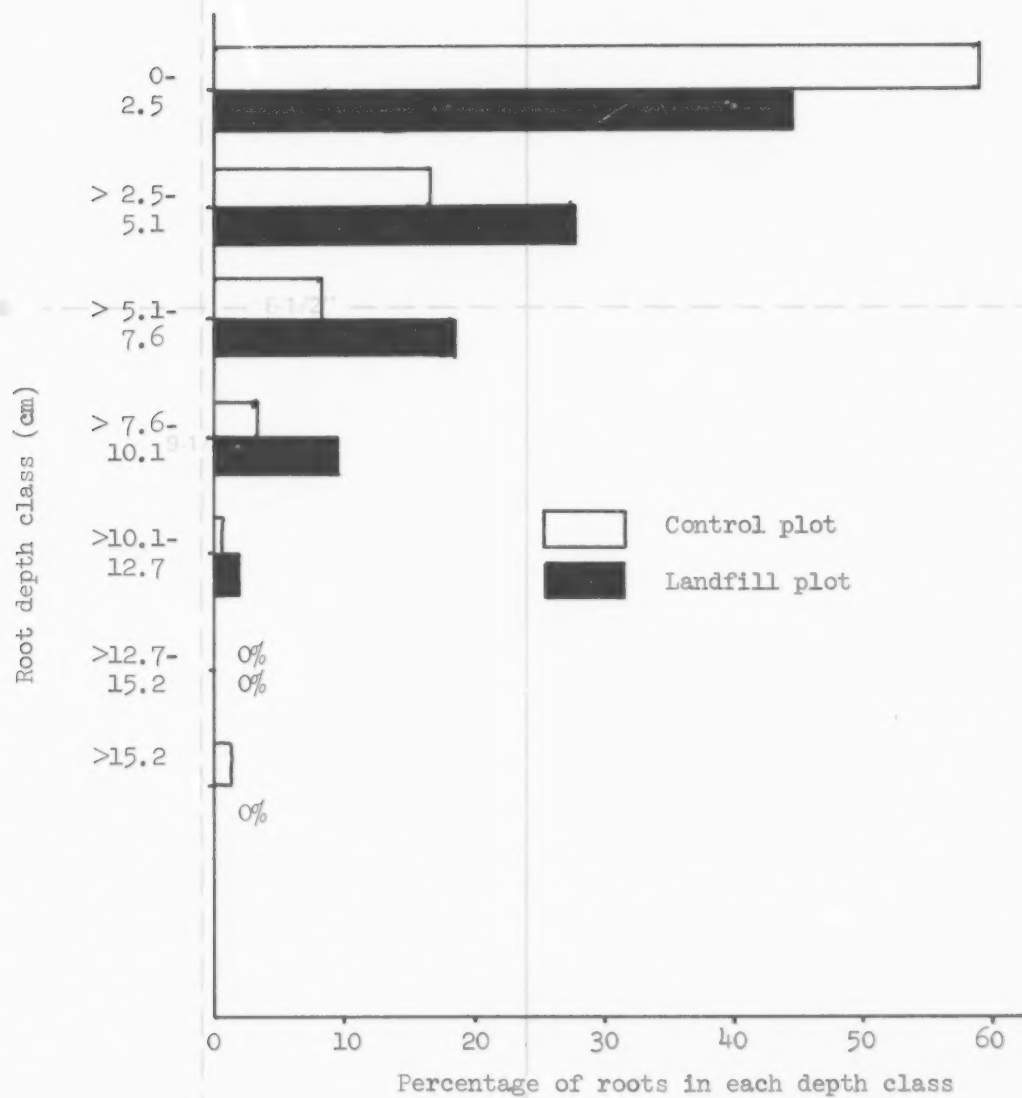


Figure 10. Vertical root distribution of Norway spruce in landfill and control plots. Each value is the mean for two trees.

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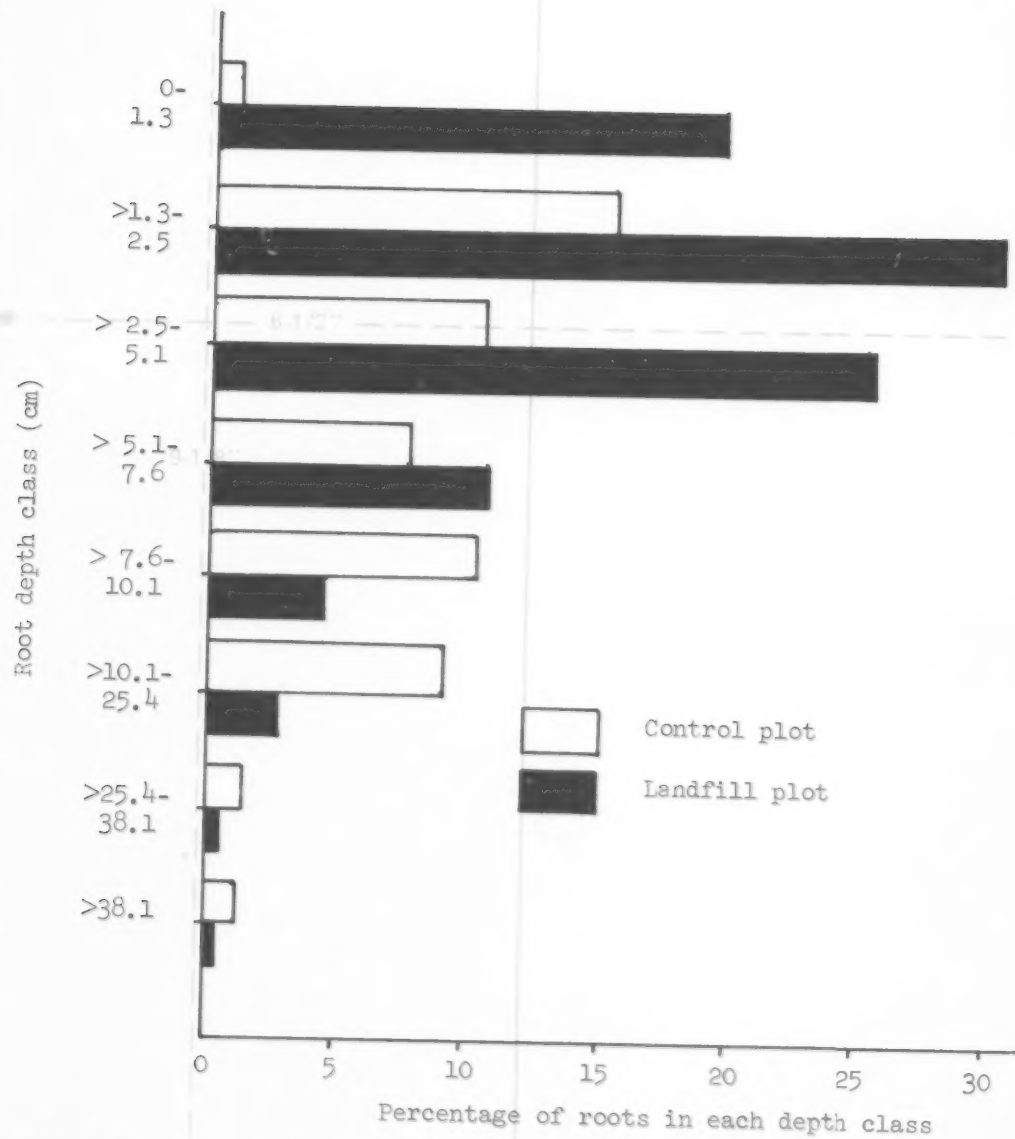


Figure 11. Vertical root distribution of hybrid poplar cuttings in landfill and control plots. Each value is the mean for two trees.

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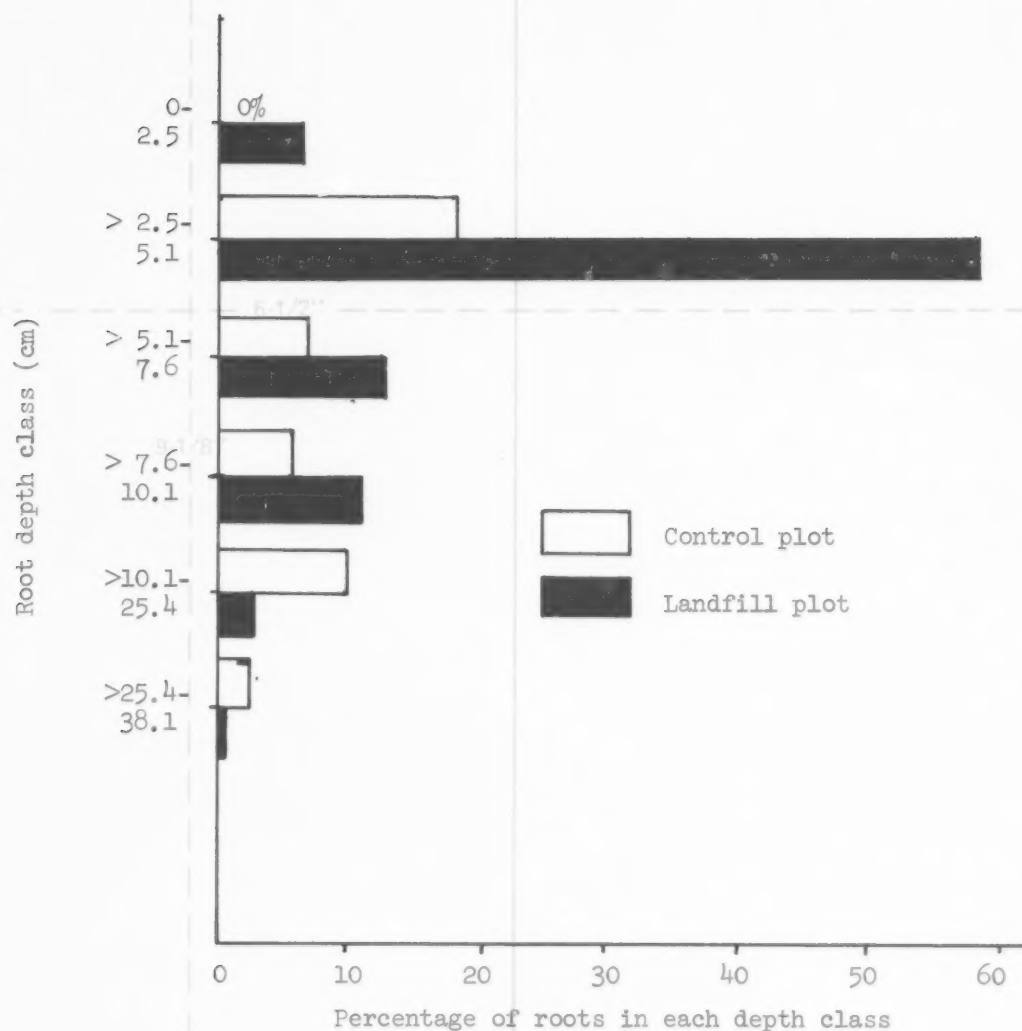


Figure 12. Vertical root distribution of honey locust in landfill and control plots. Each value is the mean for two trees.

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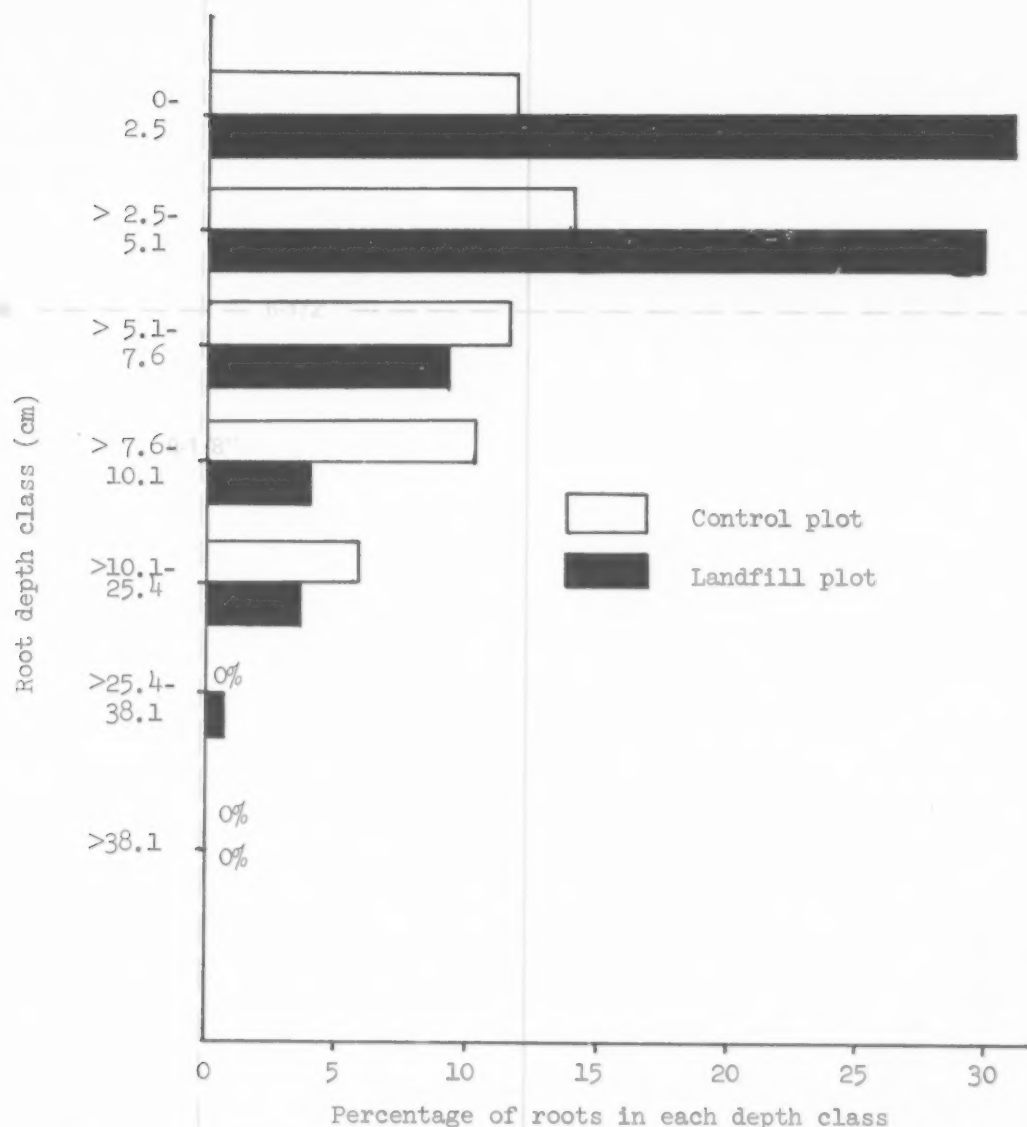


Figure 13. Vertical root distribution of green ash in landfill and control plots. Each value is the mean for two trees.

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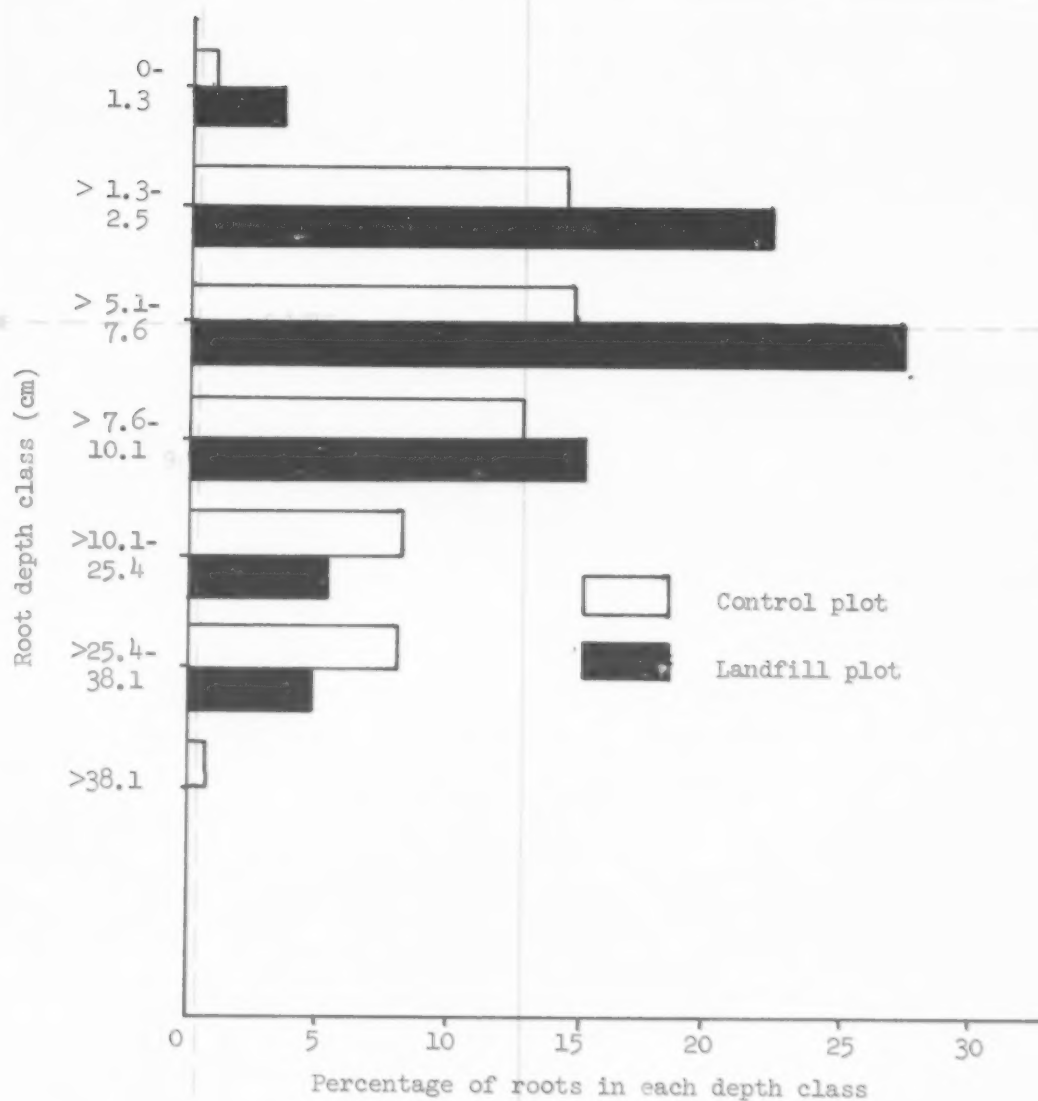


Figure 14. Vertical root distribution of hybrid poplar in landfill and control plots. Each value is the mean for two trees.

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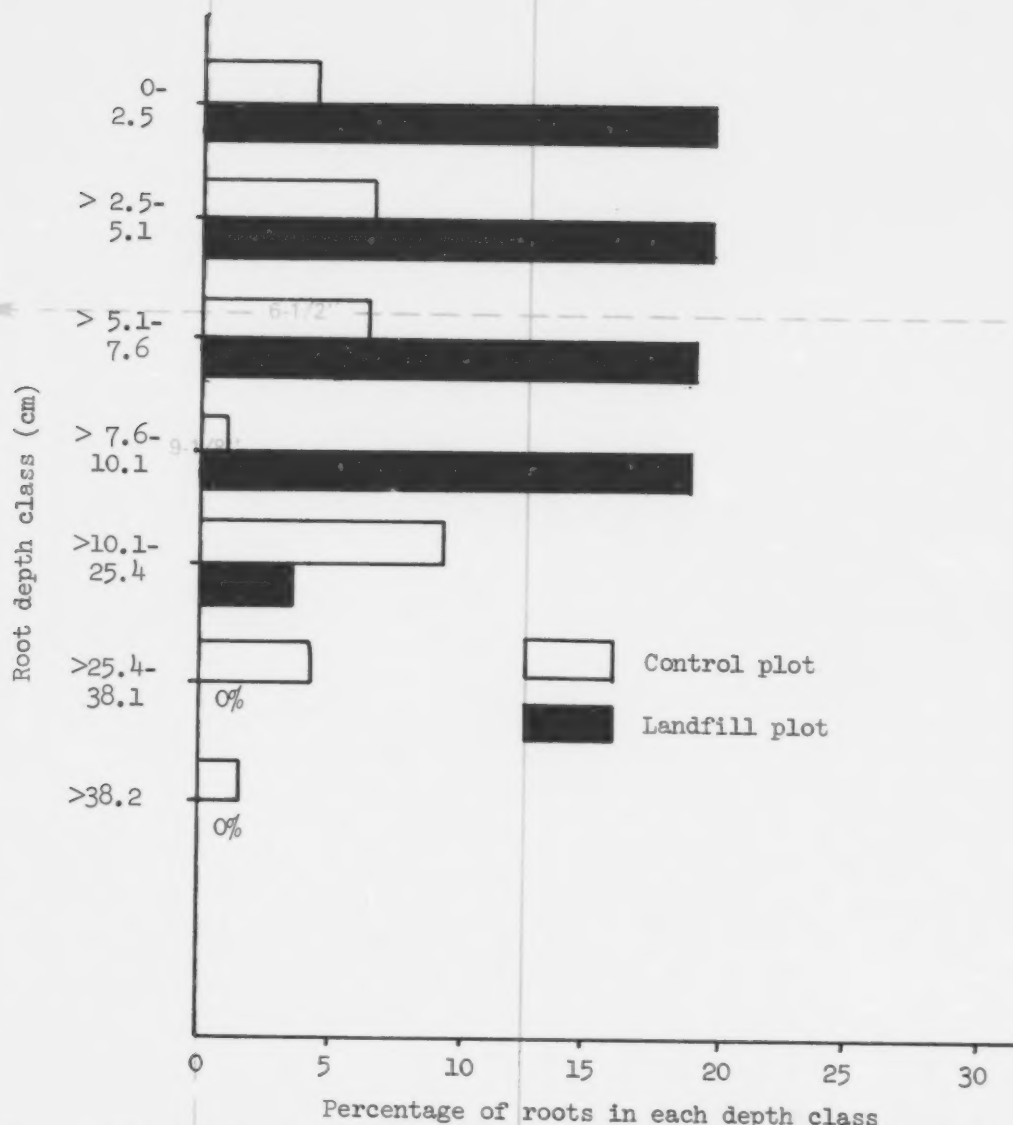


Figure 15. Vertical root distribution of small green ash in landfill and control plots. Each value is the mean for two trees.

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five-2.54 cm intervals; e.g. in order to calculate the total percentage of roots in the >25.4 cm class, multiply the bar value times five. All but one of the five species (i.e. Norway spruce) produced proportionally more roots in the upper soil layers on the landfill plot than on the control. Norway spruce on the other hand, produced approximately 58% of its root system in the top 2.5 cm of the soil; whereas, only 44% were growing at this depth in the landfill plot. More roots penetrated the deeper soil layers in the control area than in the landfill area.

The number and percentage of hybrid poplar roots at each soil depth are presented in Table 44. One of the landfill trees (Tree B, Figure 16) was located in a high-gas area where the carbon dioxide concentration during 1977, 1978 and 1979 averaged 18.1%, methane averaged 5% and oxygen averaged 15.8%. The other hybrid poplar on the landfill (Figure 17) was growing in a low-gas area where the carbon dioxide (1.4%), methane (trace) and oxygen (19.6%) concentrations were similar to concentrations around trees (Figures 18-19) in the control plot.

Root distribution of hybrid poplar cuttings in the high-gas area was significantly different from that in the low-gas landfill and control areas (Table 45). Thirty-five percent of the roots in the high-gas area were in the top 1.3 cm (0.5 in) of soil, whereas, only 3.8% were growing at this depth in the low-gas area. Less than 1.5% of the roots of the hybrid poplar in the control area were found at the 1.3 cm (0.5 in) depth. No roots were found below 25.4 cm (10 in) in the high-gas landfill area; whereas, 4.5% of the roots in the low-gas landfill area and more than 10% of the roots in the control area were found below this depth.

The black arrows in Figure 16 indicate several roots which extended into the deeper soil layers 58 cm (23 in) in the low-gas landfill area. These roots were generally closer to the trunk than were the shallower roots. None of the roots growing in the high-gas landfill (Figure 17) area extended below the 18-cm (7-in) depth. The arrow in Figure 17 indicates one root which started to grow down toward the refuse but died when it reached the 18-cm (7-in) depth. The soil at this depth was very dark in color and had a septic odor. A hole was dug at this location in order to measure the cover soil depth. Only 10-cm (4-in) of soil was found between the dead root tip and the refuse layer. Apparently, no more than 28-cm (11-in) of cover soil had been placed at this location. There was an abundance of shallow roots growing from this tree (Figure 17). Shallow roots appeared infrequently on the two poplar trees on the control plot (Figure 18 and 19), whereas, deeper roots were prevalent (black arrows in Figures 18 and 19 A and B).

The photograph in Figure 20 is of the exposed root system of the poplar tree growing in the high-gas landfill area. The large root toward the bottom of the photograph with the black dot in the center was the deepest living root on this tree. It penetrated the soil to the 15-cm (6-in) depth and then grew upward to the soil surface where it branched, producing many shallow roots. The majority of the other roots in this photograph also grew toward the soil surface. These roots grew from approximately the 10-cm (4-in) soil depth to the top 2.5 cm (1 in) of the soil surface.

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TABLE 44. NUMBER OF 30.5 cm (12 IN) HYBRID POPLAR (ROOTED CUTTINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄ AND O₂ CONCENTRATIONS AT THE 20 cm DEPTH ON LANDFILL AND CONTROL PLOTS

Soil depth in cm		Landfill				Control			
		Tree A (low)		Tree B (high)		Tree A		Tree B	
		# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
0.5	1.3	12	3.8a ⁺	98	34.9b	0	0c	5	1.4c
1	2.5	92	29.9	82	29.2	56	12.7	69	19.6
2	5.1	120	37.7	40	14.3	50	5.7	58	16.5
3	7.6	35	11.0	29	10.3	22	5.7	32	9.1
4	10.1	6	1.9	18	6.5	40	10.1	39	11.1
5	12.7	4	1.3	4	1.4	49	12.4	37	10.5
6	15.2	13	4.1	6	2.1	55	13.9	39	11.1
7	17.8	0	0	1	0.3	29	7.4	7	2.0
8	20.3	10	3.1	1	0.3	19	4.8	9	2.6
9	22.8	5	1.5	1	0.3	11	2.8	8	2.3
10	25.4	4	1.3	1	0.3	15	3.8	8	2.3
11	27.9	0	0	0	0	14	3.5	2	0.6
12	30.5	4	1.3	0	0	7	1.8	9	2.6
13	33.0	0	0	0	0	3	0.8	8	2.3
14	35.6	1	0.3	0	0	7	1.8	5	1.4
15	38.1	0	0	0	0	0	0	0	0
16	40.6	3	1.0	0	0	4	1.0	6	1.7
17	43.2	0	0	0	0	4	1.0	0	0
18	45.7	2	0.7	0	0	3	0.7	3	0.8
19	48.3	0	0	0	0	2	0.5	0	0
20	50.8	1	0.3	0	0	3	0.8	2	0.6
21	53.3	1	0.3	0	0	1	0.3	0	0
22	55.9	1	0.3	0	0	0	0	0	0
23	58.4	1	0.3	0	0	0	0	5	1.4
Total length (m)		96.0		85.6		120.1		107.0	
Mean depth (cm)		8.9		3.8		14.5		12.7	
Maximum depth (cm)		58.4		25.4		53.3		58.4	
CO ₂		1.4		18.1		1.2		1.2	
CH ₄		trace		5.0		0.0		0.0	
O ₂		19.6		15.8		19.4		19.3	

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+ Columns with similar letters have a similar root distribution by Chi-Square Analysis at P<.01.

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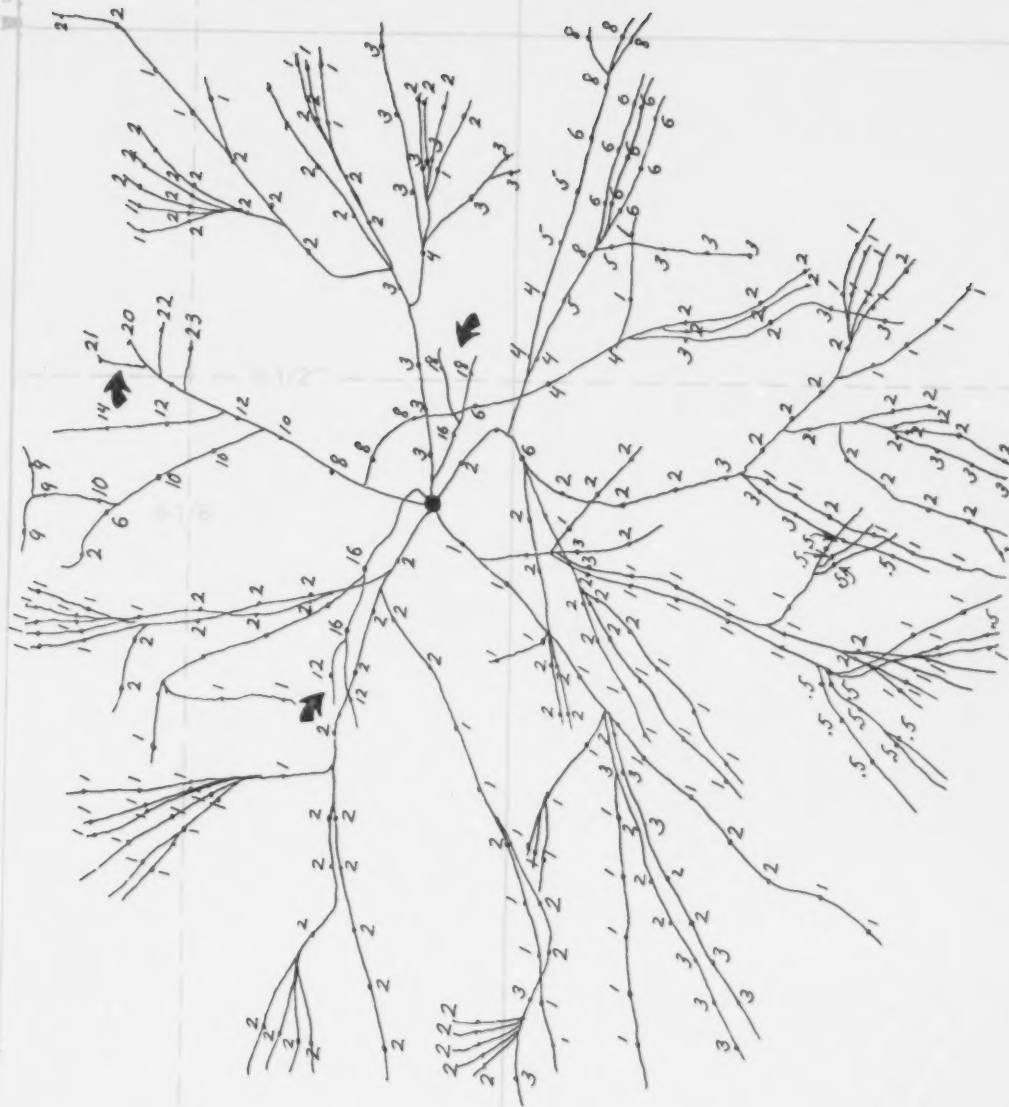


Figure 16. Diagram of hybrid poplar cutting A (low-gas) root system in landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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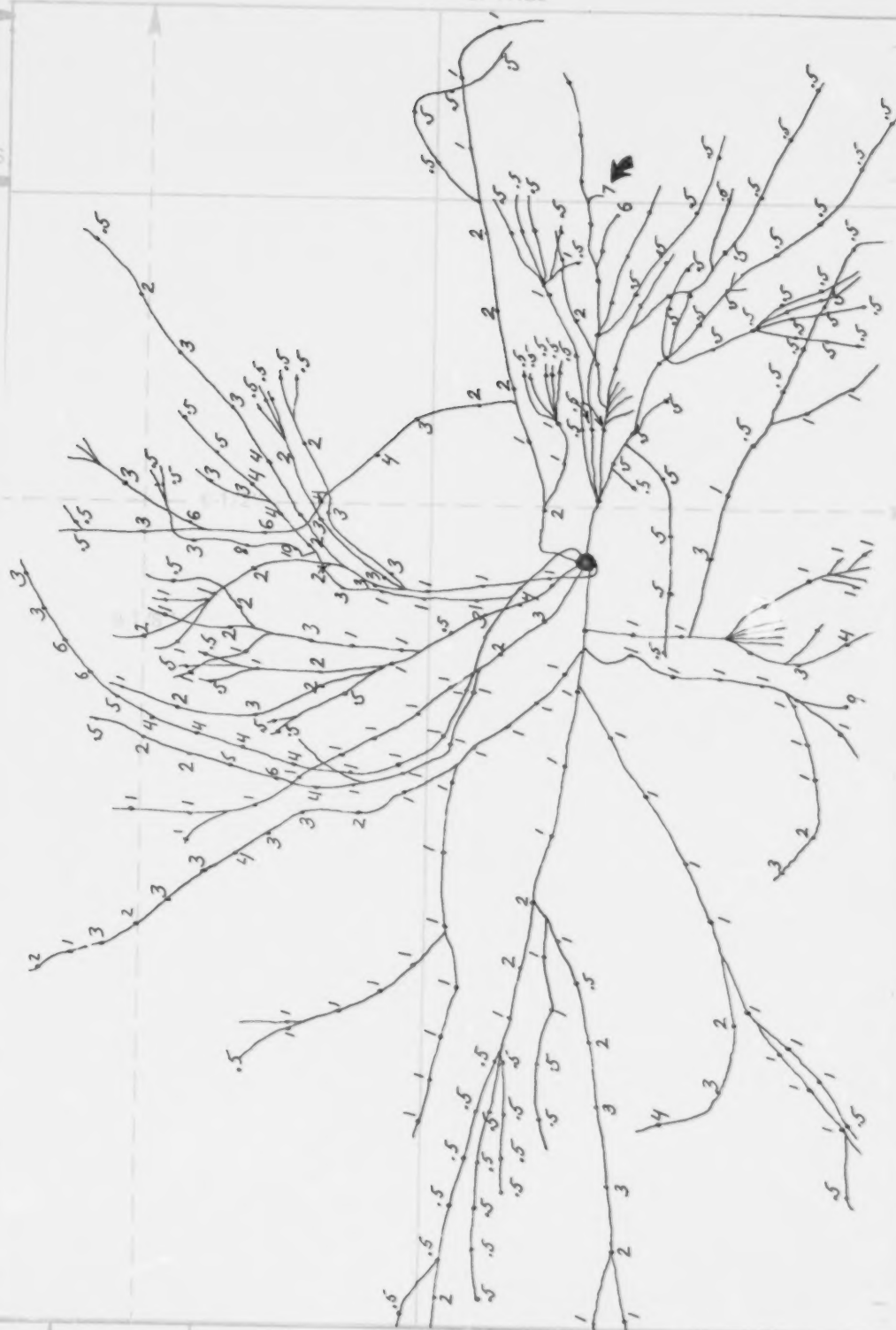


Figure 17. Diagram of hybrid poplar cutting B (high-gas) root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

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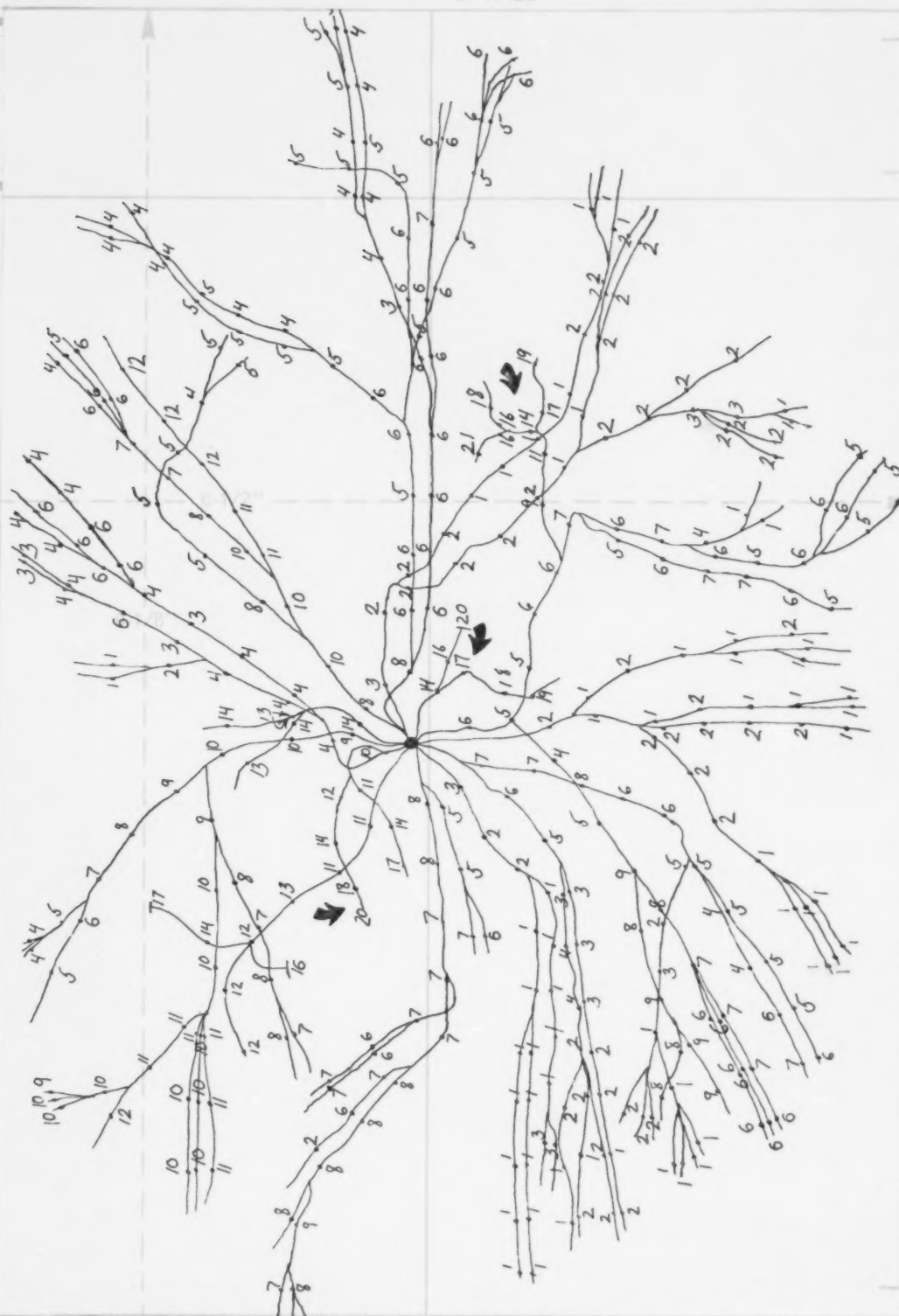


Figure 18. Diagram of hybrid poplar cutting A root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals.

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Figure 19. Diagram of hybrid poplar cutting B root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals. (continued)

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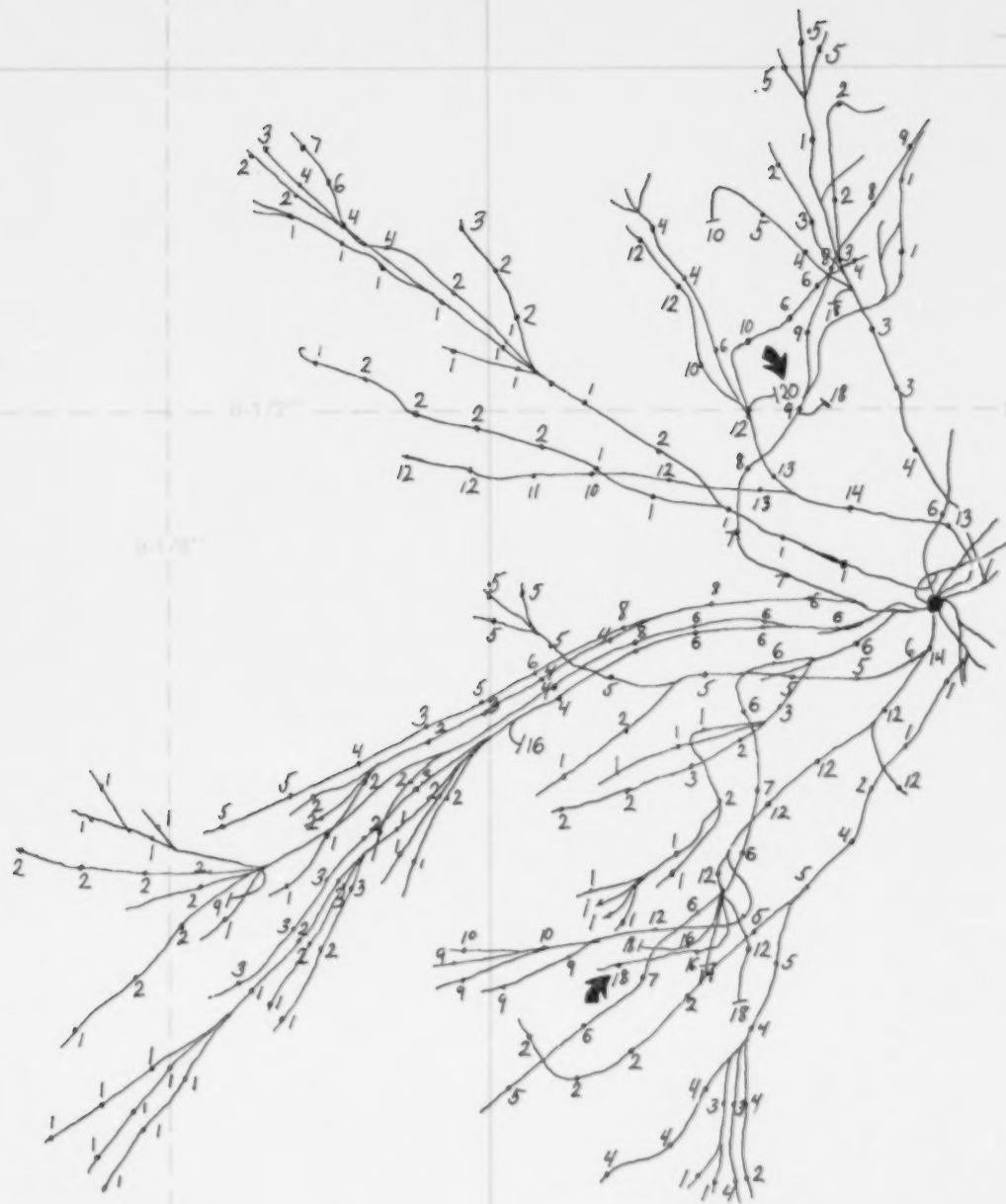


Figure 19. (continued)

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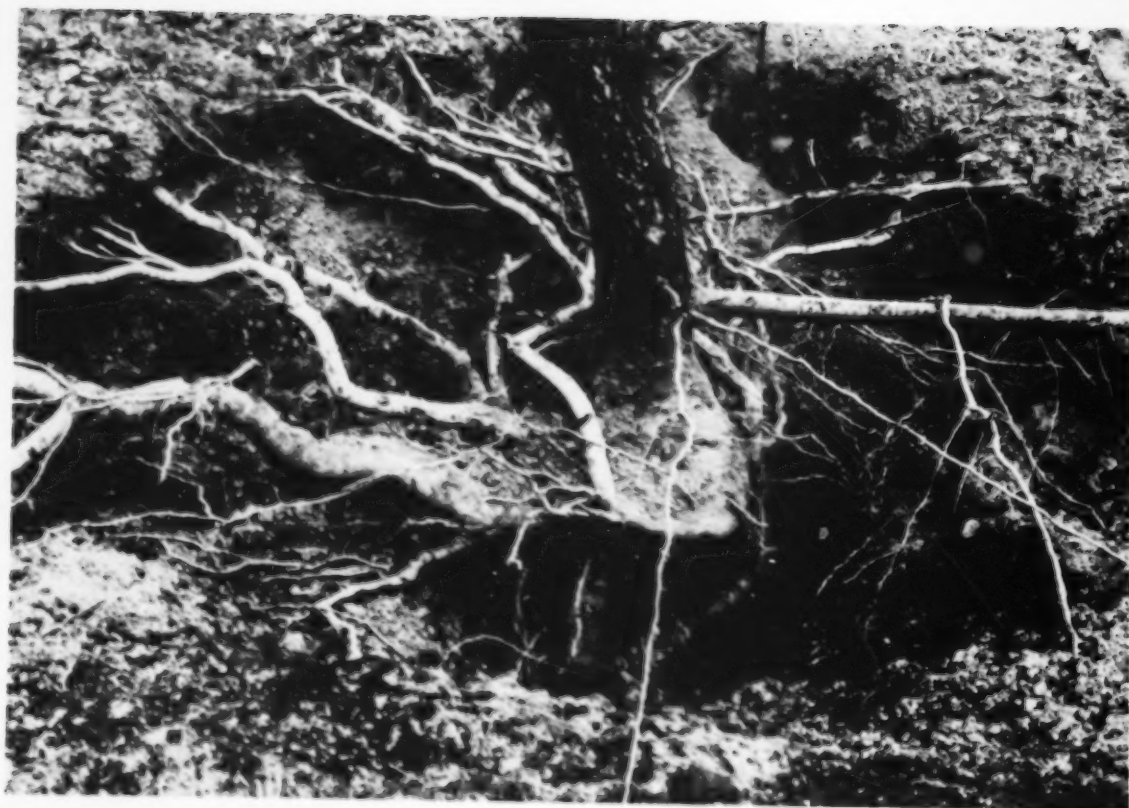


Figure 20. Root system of hybrid poplar cuttings in high gas landfill area.

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TABLE 45. PERCENTAGE OF ROOTS OF HYBRID POPLAR CUTTINGS IN EACH ROOT-DEPTH CLASS IN HIGH AND LOW GAS* AREAS

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Root depth class	Landfill		Control	
	High gas Area B	Low gas Area A	Area A	Area B
0- 1.3	34.9a ⁺	3.8b	0c	1.4c
1.3- 5.1	43.5	67.6	18.4	36.1
5.1-10.1	16.8	12.9	15.8	20.2
10.1-25.4	4.7	11.3	45.1	27.5
25.4-38.1	0	1.6	7.9	6.9
38.1-50.8	0	2.0	4.0	2.1
50.8	0	0.9	0.3	1.4

* See Table 44 for gas concentrations.

+ Columns with similar letters have similar root distributions at $P < .01$ by Chi-Square Analysis.

The arrow in Figure 21 A points to a surface root approximately 4 m (13 ft) long growing from the poplar in the high-gas area. This root originated at the 5 cm (2 in) depth and grew upward to the 2.5-cm (1 in) depth within 60 cm (24 in) of the stump and continued to elongate at this depth for approximately 3.5 m (11.5 ft). The extent of root development in the top several cm of soil in the high-gas area is exhibited in Figure 21B. Few roots in the top several cm of soil produced a sinker root; when a root reached the top several cm of soil, it generally remained at that depth and rarely branched to produce a root which grew toward the refuse.

The roots of the poplar cutting in the low-gas landfill area which penetrated to the 40-cm (16-in) depth (Table 44) are identified with arrows in Figure 22. Several other roots penetrating to soil depths greater than 50 cm (20 in) are not shown in this photograph, but are represented diagrammatically in Figure 16.

Roots of the two hybrid poplar (cuttings) trees in the control plot were more evenly distributed in the soil than those in the landfill plot; they were not as concentrated in the top soil layers as those in the landfill plot (Table 44). Figure 23 illustrates the root distribution around a hybrid poplar cutting on the control plot. The arrow in Figure 23 points to a root which is enlarged and marked with a large dot in Figure 24. The roots pictured here have grown from the soil surface straight down to approximately 50 cm (16 in). (The scale of the ruler in the photograph (Figure 24) is in inches.) Several of these roots (arrows) have become grafted to each other.

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Average poplar root depth in the high-gas area (Table 46) was considerably shallower (3.8 cm, 1.5 in) than in the low-gas area (8.9 cm, 3.5 in) and both these areas had much shallower roots (significant @ $P < .01$) than the control plot. Total root length in the landfill plot was less than in the

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Figure 21. Surface roots of hybrid poplar in high-gas area on landfill plot.

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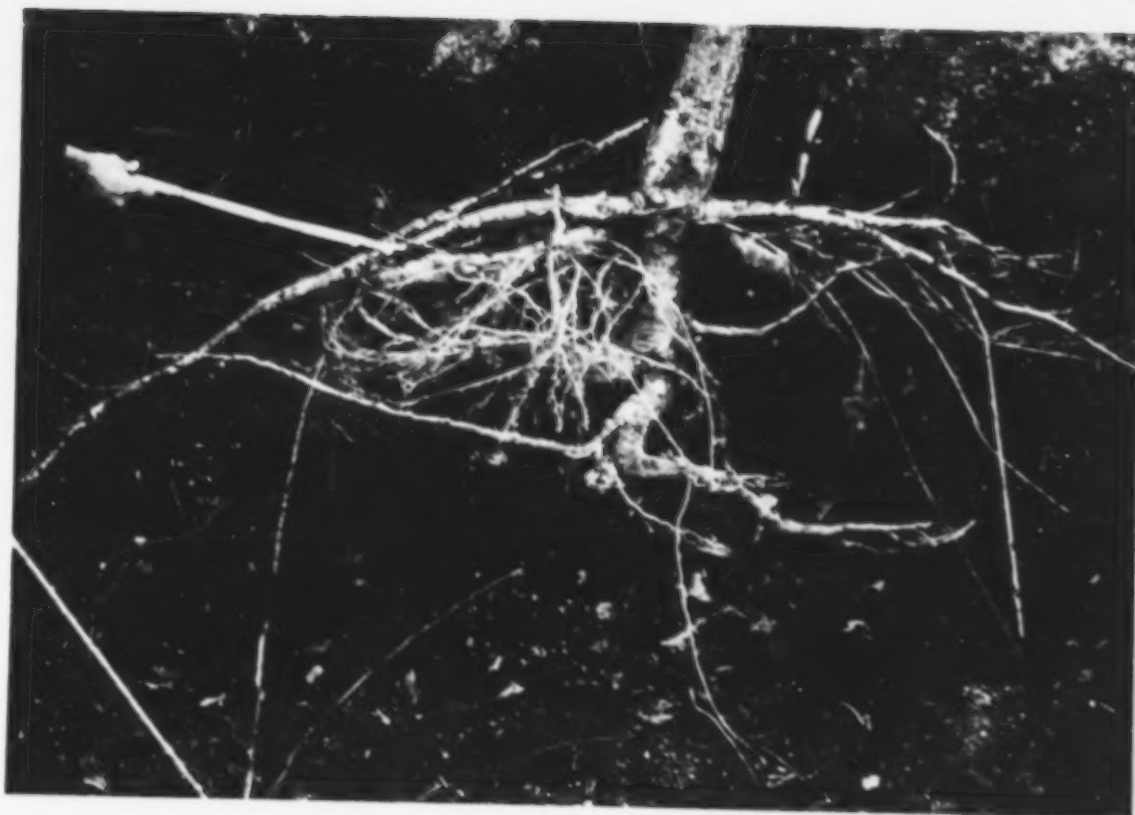
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Figure 22. Root system of hybrid poplar cutting in low-gas landfill area.

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Figure 23. Root system of hybrid poplar cuttings on control plot.

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Figure 24. Close-up of hybrid poplar cutting root system on control plot.

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TABLE 46. MEAN ROOT DEPTH AND TOTAL ROOT LENGTH FOR HYBRID POPLAR CUTTINGS ON LANDFILL AND CONTROL PLOTS

Location	Average Root depth (cm)	Total Root length (m)
Landfill Plot*		
Low-gas area	8.9	96.0
High-gas area	3.8	85.6
Control Plot ⁺		
Area A	14.5	120.1
Area B	12.7	107.0

* Carbon dioxide averaged 18.1% at the 20 cm (8 in) depth in the high-gas area and 1.4% at the 20 cm (8 in) depth in the low-gas area from 1976 through 1979.

+ Carbon dioxide averaged 1.1% at the 20 cm (8 in) depth from 1976 through 1979.

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Root systems of the four excavated green ash seedlings (2 years old when planted) are diagrammed in Figures 25 through 28. Green ash seedling A (Figure 25) on the landfill plot was growing in an area where the carbon dioxide averaged 5.2%, methane averaged 1.9% and oxygen averaged 19.8% during 1977, 1978 and 1979. The other excavated landfill tree (B) (Figure 26) was growing in an area where the carbon dioxide concentration averaged 14.7%, methane 6.1% and oxygen 16.1%. Carbon dioxide averaged 1.1%, oxygen averaged 19.8% and methane was never detected in the control plot.

The roots of green ash B growing in the high-gas landfill area were concentrated near the soil surface (Table 47) and (Figure 29C), whereas roots of ash A growing in a low-gas landfill area (Figure 29B) penetrated to slightly deeper depths (Table 47). On the other hand, few roots on control trees were found in the top 10.1 cm (4 in).

A close-up photograph of the lower portion of the ash root system in the low-gas landfill area (Figure 30B) depicts an abundance of short roots at about the 20-cm (8-in) depth. The soil immediately below this short root zone was darker than the surrounding soil and was giving off a septic odor. No odor was detected in the soil above this point. Short root formation was not as noticeable on the ash growing in the high-gas area on the landfill (Figure 30A).

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Root depth and length values for ash growing in both the high and low landfill gas areas were approximately half the values of the control (Table 48). There was little difference in depth and length between the two trees

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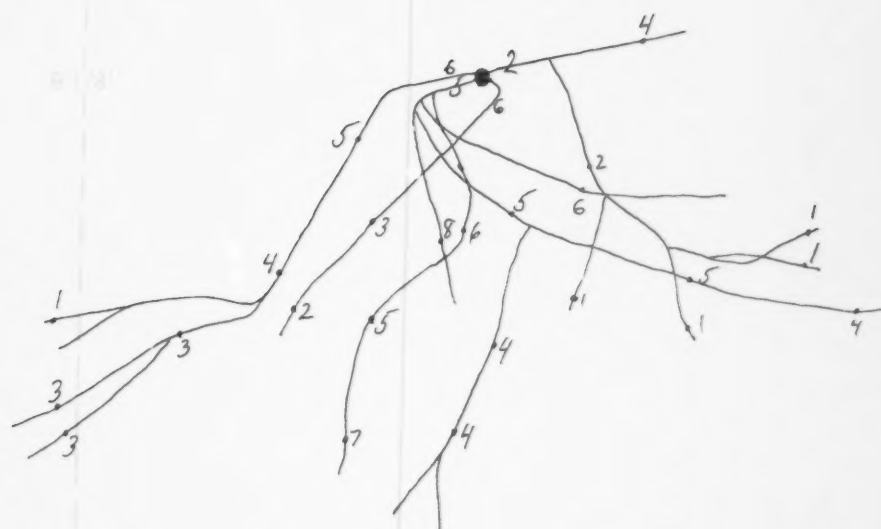


Figure 25. Diagram of green ash seedling A root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

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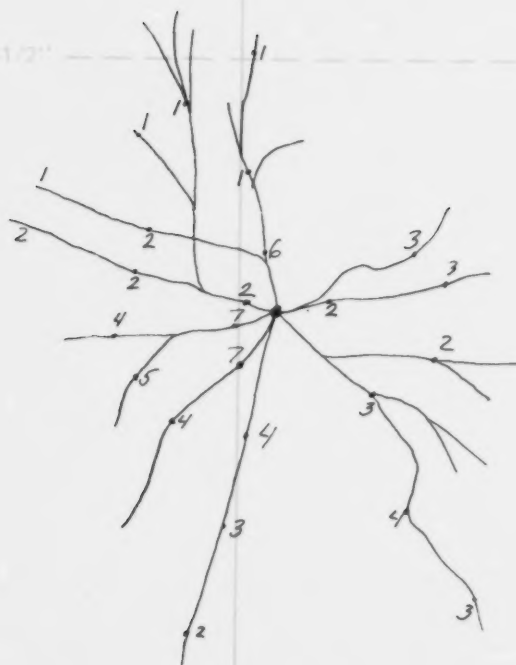


Figure 26. Diagram of green ash seedling B root system in landfill plot indicating root depth in inches at 30.5-cm (12-in) intervals.

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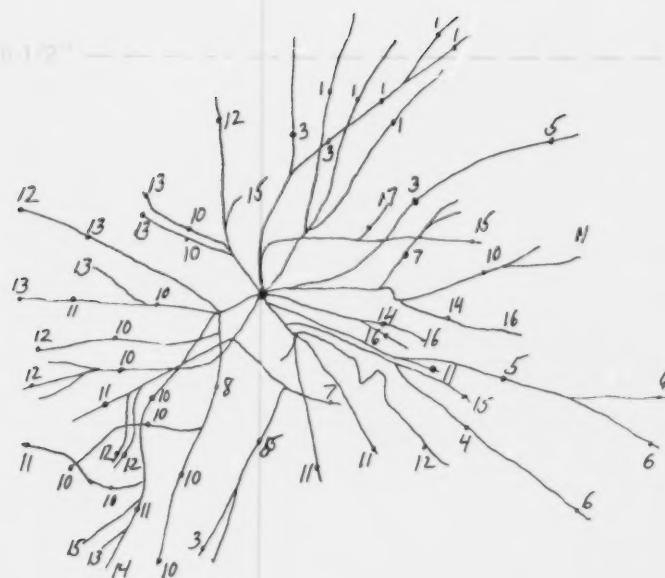


Figure 27. Diagram of green ash seedling A root system in control plot indicating root depth in inches at 30.5-cm (12-in) intervals.

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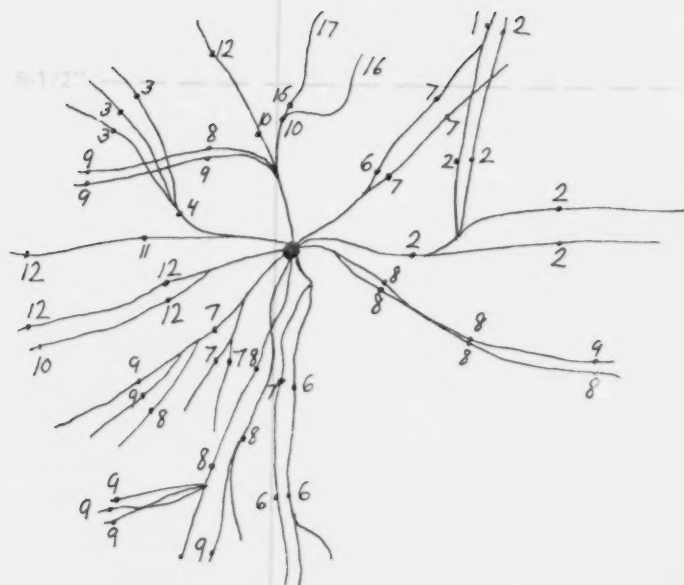


Figure 28. Diagram of green ash seedling B root system on control plot indicating root depth at 30.5-cm (12-in) intervals.

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TABLE 47. NUMBER OF 30.5-cm (12-IN) GREEN ASH (SMALL TREES) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄ AND O₂ CONCENTRATION ON LANDFILL AND CONTROL PLOTS²

Soil depth in cm		Landfill				Control			
		Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
		# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
1	2.5	5	16.7b ⁺	5	20.0c	6	8.8a	0	0a
2	5.1	3	10.0	7	28.0	1	1.4	6	11.5
3	7.6	5	16.7	5	20.0	5	7.1	3	5.8
4	10.1	6	20.0	4	16.0	1	1.4	1	1.9
5	12.7	5	16.7	1	4.0	5	7.1	0	0
6	15.2	4	20.0	1	4.0	4	5.7	3	5.8
7	17.8	1	16.7	2	8.0	5	7.1	7	13.6
8	20.3	1	13.1	0	0	3	4.3	9	17.3
9	22.8	0	3.4	0	0	0	0	12	23.0
10	25.4	0	3.4	0	0	10	14.4	3	5.8
11	27.9	0	0	0	0	8	11.4	1	1.9
12	30.5	0	0	0	0	8	11.4	5	9.6
13	33.0	0	0	0	0	4	5.7	0	0
14	35.6	0	0	0	0	4	5.7	0	0
15	38.1	0	0	0	0	3	4.3	0	0
16	40.6	0	0	0	0	2	2.8	1	1.9
17	43.2	0	0	0	0	1	1.4	1	1.9
Total length (m)		9.1		7.6		21.3		15.8	
Mean depth (cm)		9.6		7.6		22.6		19.8	
Maximum depth (cm)		20.3		17.8		43.2		43.2	
CO ₂		5.2		14.7		1.1		1.1	
CH ₄		1.9		16.1		0.0		0.0	
O ₂		17.8		6.1		19.8		19.8	

+ Columns with different letters have statistically different distribution by Chi-Square Analysis at P<.01.

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Figure 29.

Root systems of green ash seedlings on control (A), low-
gas (B), and high-gas (C) landfill plots.

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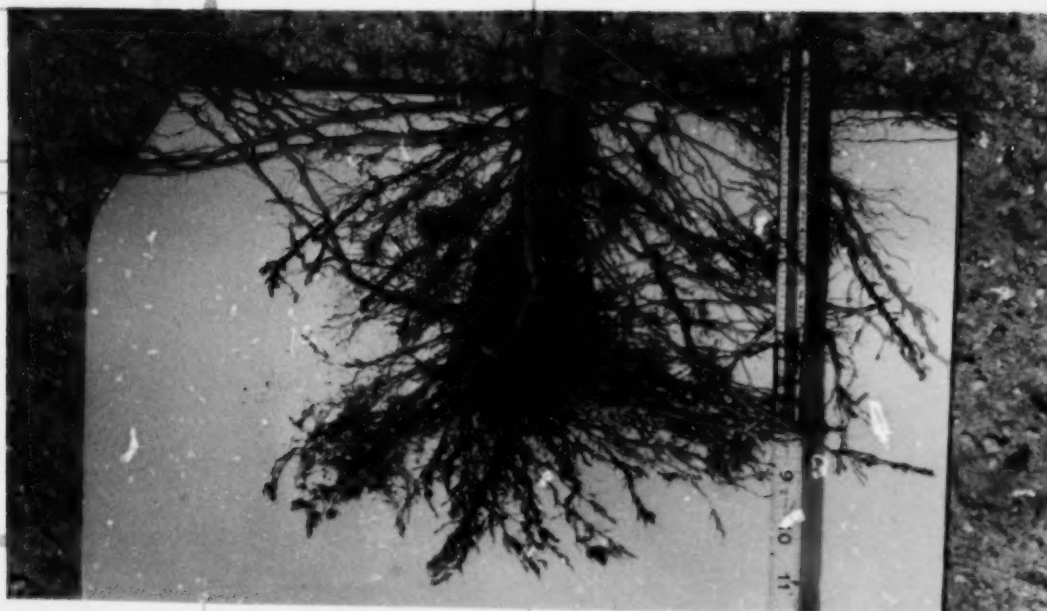
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Figure 30. Close-up photographs of root systems of green ash seedlings on landfill high gas (A) and landfill low-gas (B) plots.

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On the control plot. Ash seedlings on the control area did not form the matted short-root zone found on the landfill trees. Several control tree roots, like the one shown in Figure 31 (arrow), grew almost straight down. This was not found on the landfill trees.

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TABLE 48. MEAN ROOT DEPTH AND TOTAL ROOT LENGTH FOR SMALL GREEN ASH IN HIGH GAS AND LOW GAS AREAS ON LANDFILL PLOT AND IN TWO AREAS ON CONTROL PLOT

Location	Mean Root depth (cm)	Total Root length (m)
Landfill*		
Low gas area A	9.6	9.1
High gas area B	7.6	7.6
Control ⁺		
Area A 6-1/2"	22.6	21.3
Area B	19.8	15.8

* Carbon dioxide in the high-gas area averaged 14.7% at the 20 cm (8 in) depth and in the low gas area 5.2% at the 20 cm (8 in) depth from 1978 through 1979.

+ Carbon dioxide averaged 1.1% at the 20 cm (8 in) depth from 1978 through 1979.

The root systems of four large green ash saplings, two on the landfill and two on the control plot were excavated. The number of roots at each soil depth is given in Table 49. Tree A (diagrammed in Figure 32) growing in a low-gas area where the CO₂ concentrations during 1977, 1978 and 1979 averaged 3.9%, CH₄ averaged 1.3% and O₂ averaged 18.3% produced a mat of short roots at the 25-cm (10-in) depth illustrated in Figures 33A and B. Immediately below the root mat was a dark soil layer which had the odor of decomposing refuse (arrows, Figure 33B). A less-dense mat-like formation was found on ash sapling B (Figure 34) in the high-gas landfill area (CO₂=13.1%, CH₄=7.3%, O₂=12.3%); however, a large portion of the roots (46.7%) was found in the top 2.5 cm (1 in) of soil (arrows, Figure 34 and Figure 35). The large diameter roots in the center of Figure 34 were present when the tree was planted in 1976, so they were not included in any data analysis.

Control ash root systems were very well developed (Figures 36A and B and 37). The roots of control ash were more evenly distributed depthwise in the soil than those of tree A and tree B in the low-and high-gas landfill areas (Table 49). Mean root depth (6.6 cm) (Table 49) was shallower and total root length (32.0 m) lower in tree B in the high-gas area than in tree A in the low-gas landfill area and both were reduced compared to the control (Table 49).

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Figure 31. Root system of green ash seedling A on the control plot.

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Figure 32. Diagram of large green ash sapling A root system on landfill indicating root depth at 30.5-cm (12-in) intervals.

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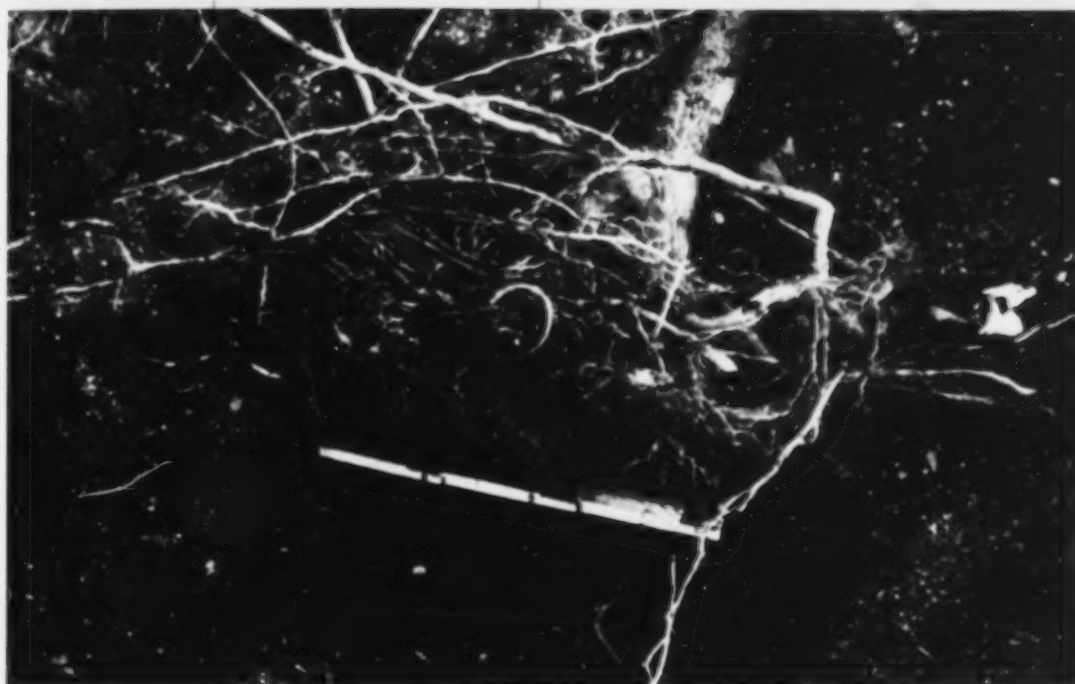
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Figure 33. Root system of green ash sapling B on low-gas landfill plot.

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Figure 34. Root system of green ash sapling B on high-gas landfill plot.

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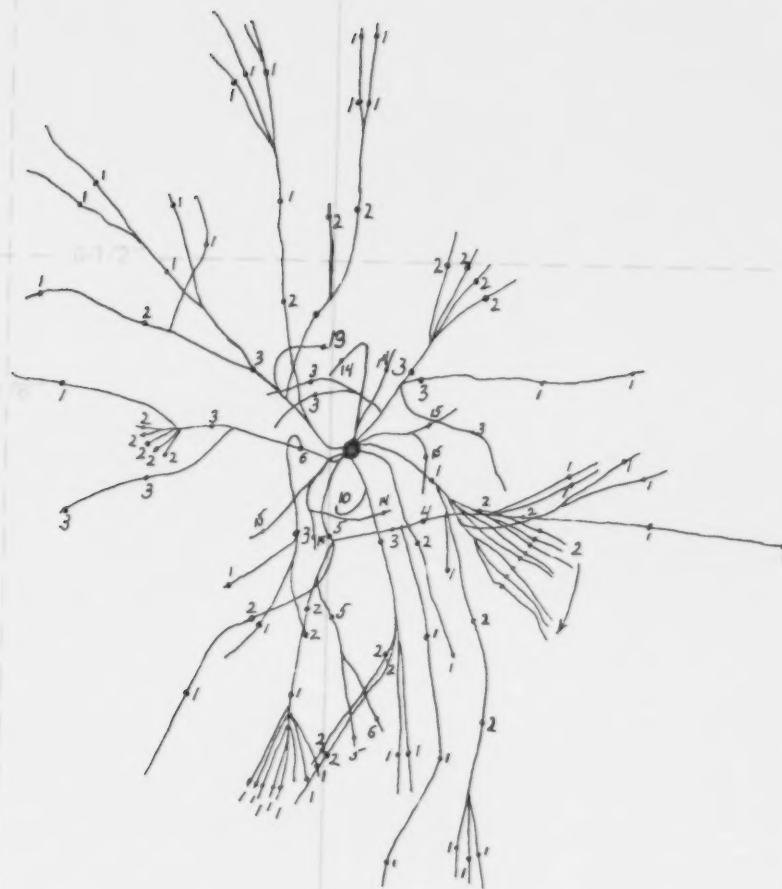


Figure 35. Diagram of green ash sapling B root system on high-gas land-fill plot indicating root depth at 30.5-cm (12-in) intervals.

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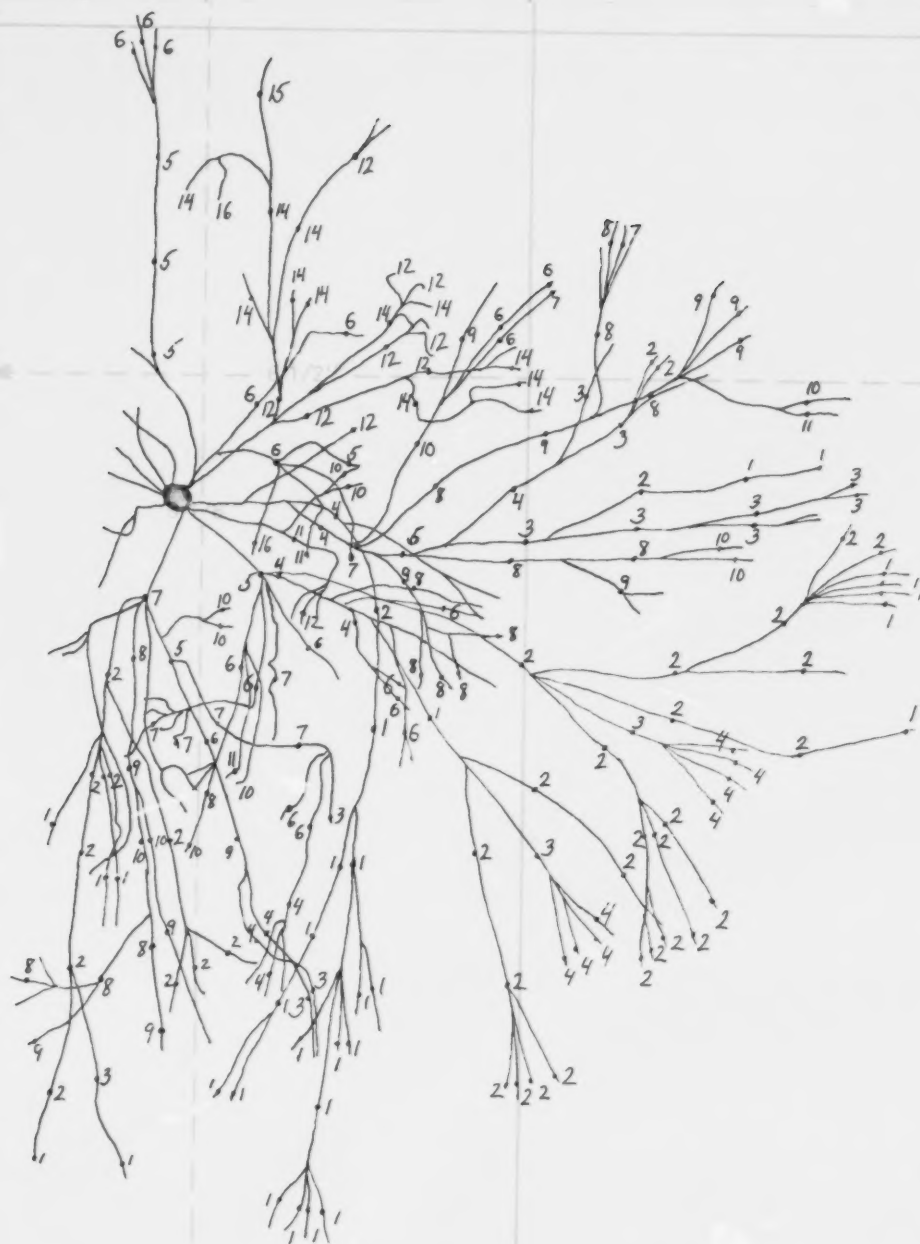


Figure 36. Diagram of green ash sapling A root system on the control plot indicating root depth at 30.5-cm (12-in) intervals. (continued)

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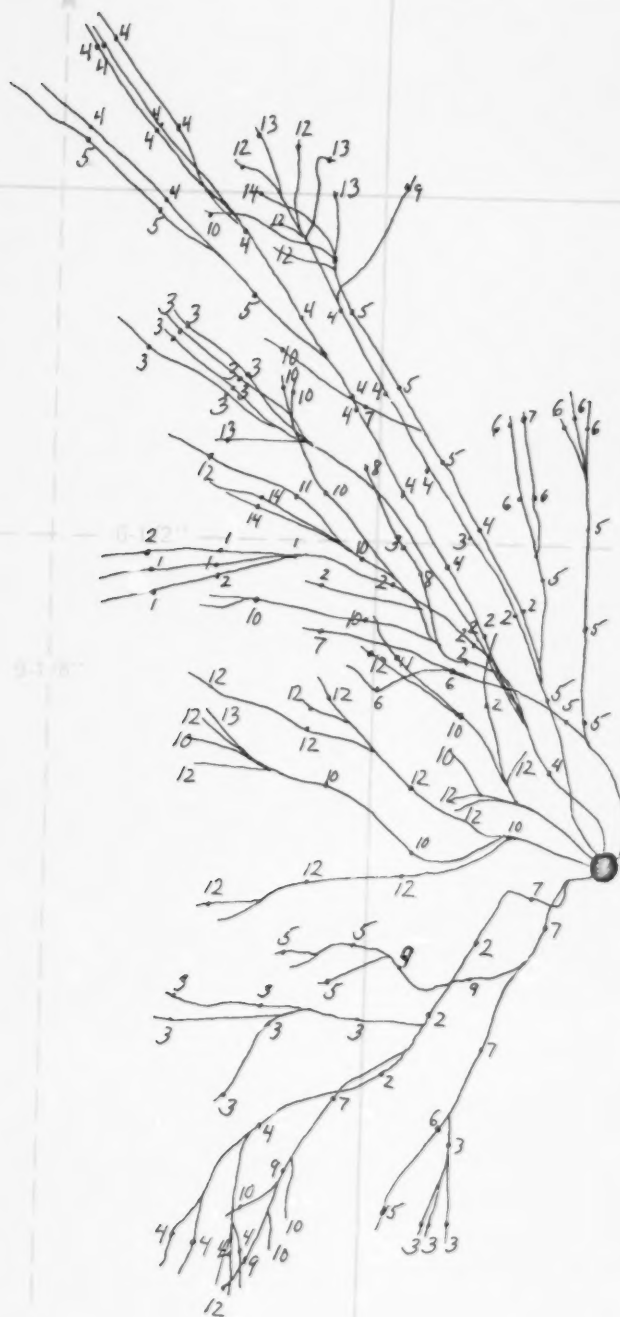


Figure 36. (continued)

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Figure 37. Root system of green ash sapling A on control plot.

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TABLE 49. NUMBER OF 30.5-cm (12-IN) LARGE GREEN ASH (SAPLINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄, O₂ CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

Soil depth in cm	Landfill				Control			
	Tree A (low gas)		Tree B (high gas)		Tree A		Tree B	
	# of root sections	%	# of root sections	%	# of root sections	%	# of root sections	%
1 2.5	29	15.3a ⁺	49	46.7b	38	12a	36	11.9a
2 5.1	50	26.1	34	32.2	49	15.5	38	12.6
3 7.6	14	7.4	10	9.5	30	9.5	45	14.9
4 10.1	15	7.9	0	0	37	11.7	27	8.9
5 12.7	10	5.3	2	1.9	19	6.0	26	8.6
6 15.2	14	7.4	1	1.0	25	7.9	17	5.6
7 17.8	10	5.3	0	0	19	6.0	11	3.6
8 20.3	19	10.0	0	0	9	2.8	10	3.3
9 22.8	9	3.2	0	0	10	3.2	22	7.3
10 25.4	12	6.3	1	1.0	26	8.2	11	3.6
11 27.9	6	3.2	0	0	7	2.2	28	9.3
12 30.5	5	2.6	0	0	28	8.8	18	6.0
13 33.0	0	0	1	1.0	4	1.3	7	2.3
14 35.6	0	0	4	3.8	13	4.1	6	2.0
15 38.1	0	0	3	2.9	1	0.3	0	0
16 40.6	0	0	0	0	2	0.6	0	0
Total length (m)	57.9		32.0		96.6		92.0	
Mean depth (cm)	11.9		6.6		14.7		14.7	
Maximum depth (cm)	30.5		38.1		40.6		35.6	
CO ₂	3.9		13.1		1.2		1.1	
O ₂	18.3		12.3		19.8		19.6	
CH ₄	1.3		7.3		0.0		0.0	

+ Columns with similar letters have a similar root distribution by Chi-Square analysis at P<.01.

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The roots of two hybrid poplar saplings were excavated on the landfill plot; one (tree B) was in a high-gas area where the CO₂ concentration at the 20-cm (8-in) soil depth during the years 1977, 1978 and 1979 averaged 7.9%; CH₄ averaged 1.8%; and O₂ averaged 17.1%. The other landfill tree (A) was in a low-gas area (CO₂=1.2%, CH₄=0.0%; O₂=19.1%) (Table 50). Two poplar saplings were also excavated on the control plot (Table 50). The concentrations of CO₂, CH₄ and O₂ on the control were 1.2%, 0.0% and 19.1%, respectively. The poplar in the high-gas area, which died by September 1979, (Figure 38A), had made poor growth compared to the control poplars (Figure 38B) during each of the four years it remained alive. Many poplar roots at the base of this landfill tree (B) had died before root excavation operations began. The four roots which remained alive (arrows, Figure 39) originated from the stump at the 15-cm (6-in) depth or greater and grew toward the soil surface. The ends of each of these four roots were located in the top 2.5-cm (1-in) of soil (Figure 40). Most of the remaining roots in Figure 39 were dead at the time of excavation.

Most poplar roots in the low-gas area also grew toward the soil surface (Figure 41). An example of one root growing straight up toward the soil surface is indicated by the arrows in Figures 41 and 42. This root originated (arrow at top of picture) from the root stock at the 30-cm (12-in) depth and grew straight upward (arrow at middle of upward riser) to the two in (5 cm) soil depth.

Roots of excavated control poplar trees did not tend to grow toward the soil surface as did roots on the landfill areas as evidenced by the root depth values in Figures 43 and 44. Deep roots which were scarce in the landfill area were not uncommon in the control plot. The roots of a control poplar (Tree A) at the base of the rule in Figure 45 are approximately 25 cm (10 in) deep. Mean root depth for both the landfill trees was less than that in the control area (Table 50). Total root length for poplar in the high-gas landfill area was less than half of that in the low-gas area and poplars in both landfill areas produced less total root length than both poplars in the control area.

Carbon dioxide concentrations in the vicinity of two honey locust trees which were later excavated, averaged 5.5% at the 20-cm (8-in) depth during 1977, 1978 and 1979; CH₄ and O₂ in the soil substrate of honey locust in the control plot were 1.1%, 0.0%, and 18.9%, respectively.

The majority of roots on both landfill trees were found in the top 5-cm (2-in) of soil (Table 51, Figures 46 and 47). Many roots reached toward the soil surface as they grew away from the trunk. The arrows in Figure 47 and 48 point to a 3.6 m long root extending away from the trunk shown in the foreground. This root originated at the 5-cm (2-in) depth on the root stock and grew at this level throughout it's entire length.

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The root systems of the two excavated control honey locust trees (Table 51) were approximately twice as deep and more than twice as long as the trees on the landfill. The roots of control trees were fairly evenly distributed throughout the soil depths; however, locust roots on the landfill were concentrated near the surface. Roots on the control trees did not rise

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Figure 38. Hybrid poplar trees on landfill (A) and control (B) plots.

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Figure 39. Root system of hybrid poplar sapling on landfill plot.

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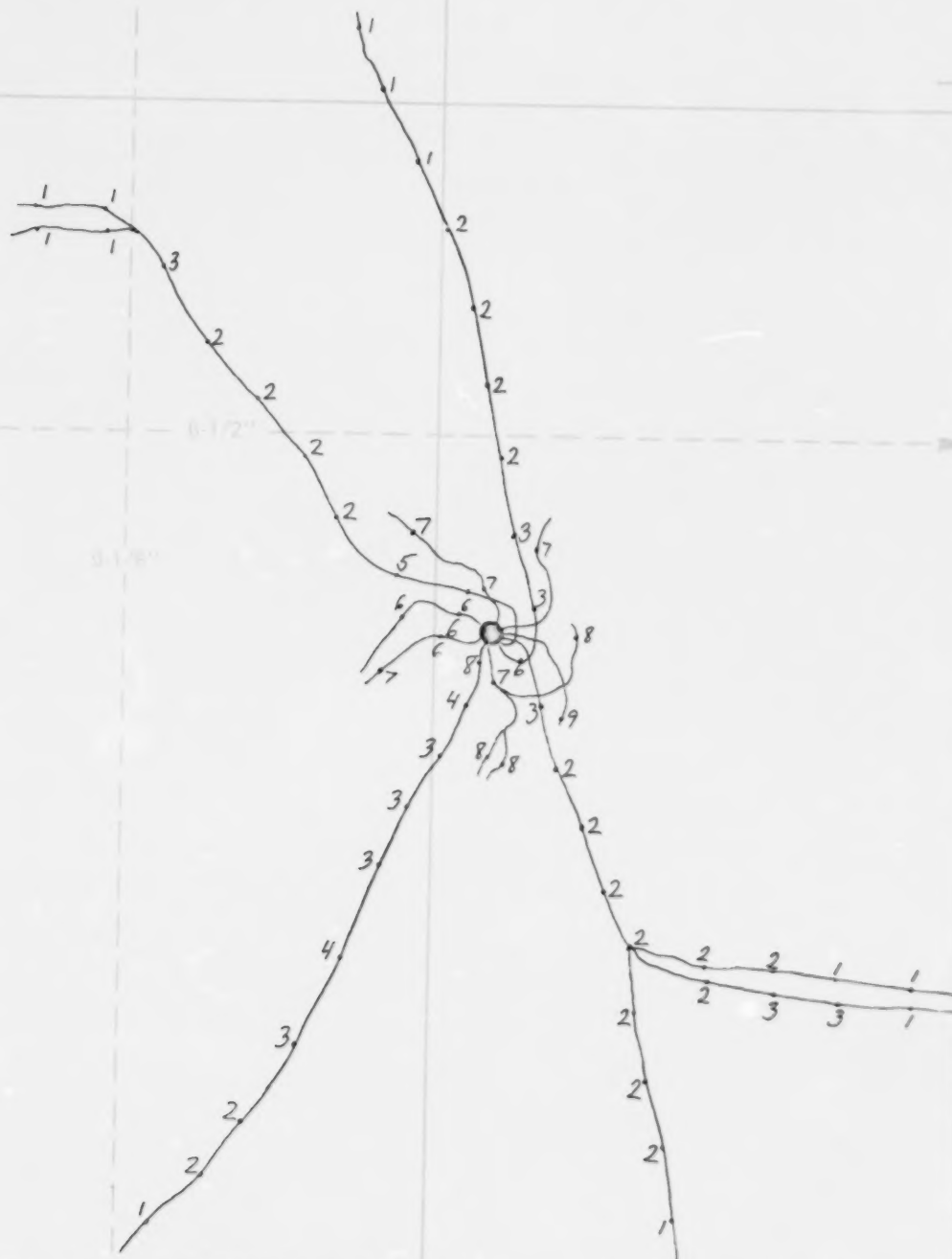
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Figure 40. Diagram of hybrid poplar sapling B root system on the high-gas landfill plot indicating root depth at 30.5-cm (12-in) intervals.

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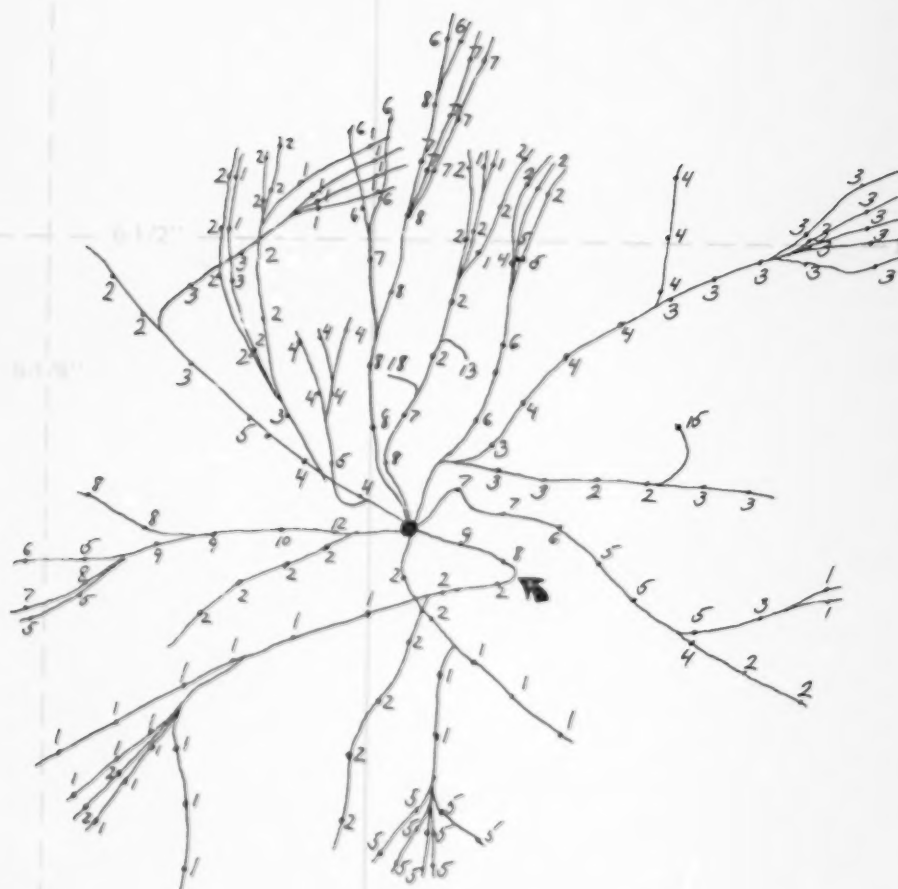


Figure 41. Diagram of hybrid poplar sapling A root system on the landfill low-gas plot indicating root depth at 30.5-cm (12-in) intervals.

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Figure 42. Root system of hybrid poplar sapling A on landfill low-gas plot.

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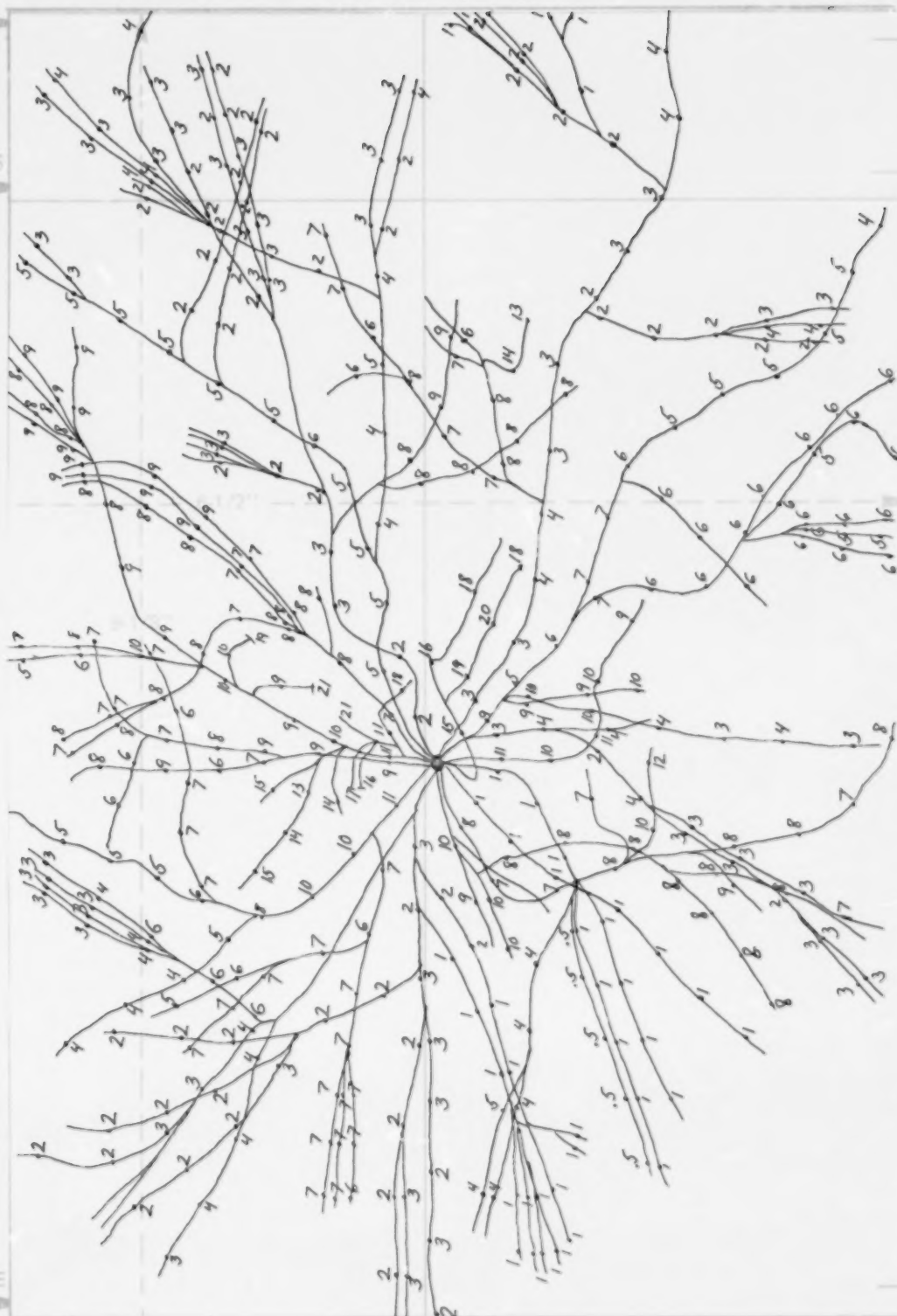


Figure 43. Diagram of hybrid poplar sapling A roots system on control plot indicating root depth at 30.5-cm (12-in) intervals.

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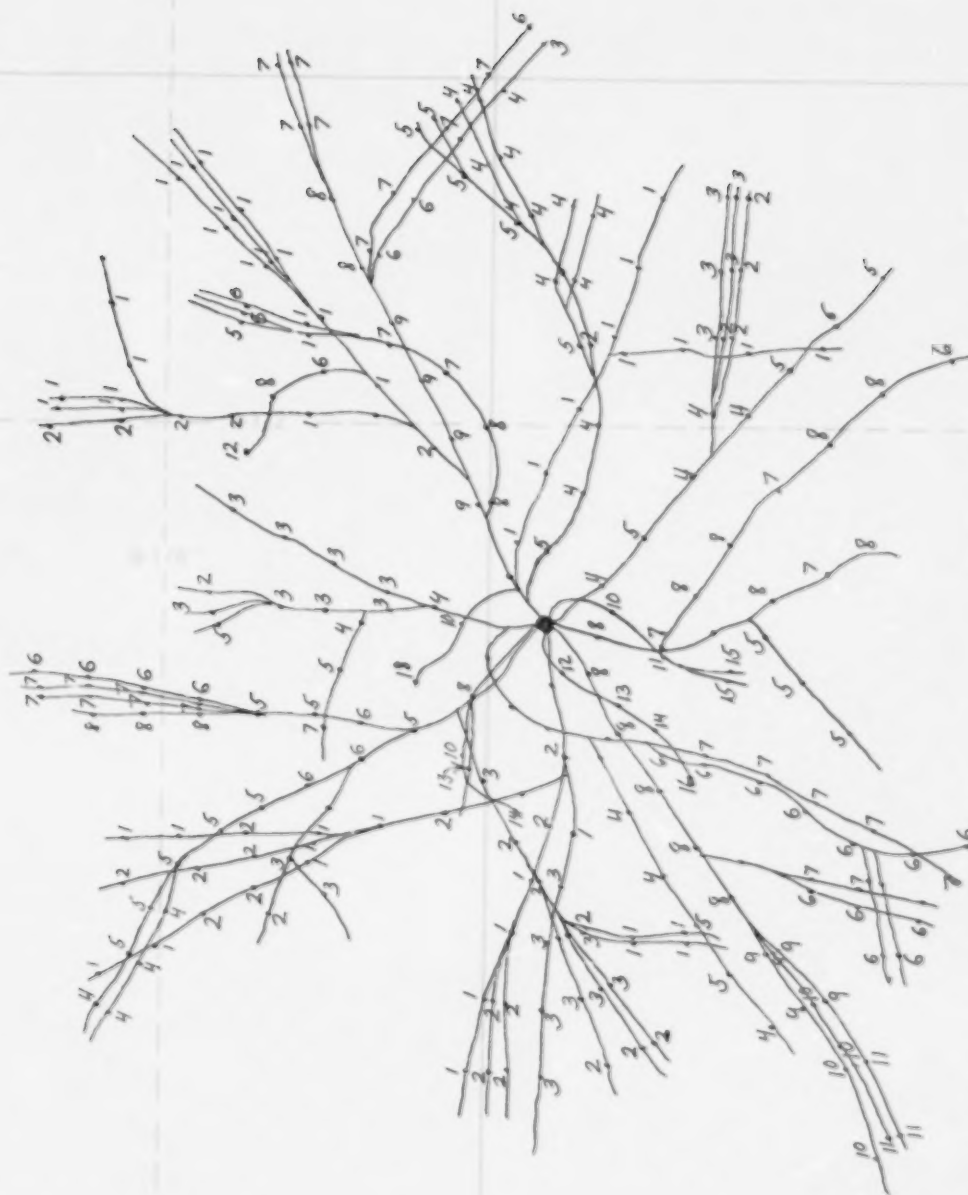


Figure 44. Diagram of hybrid poplar sapling B root system on control plot indicating root depth at 30.5-cm (12-in) intervals.

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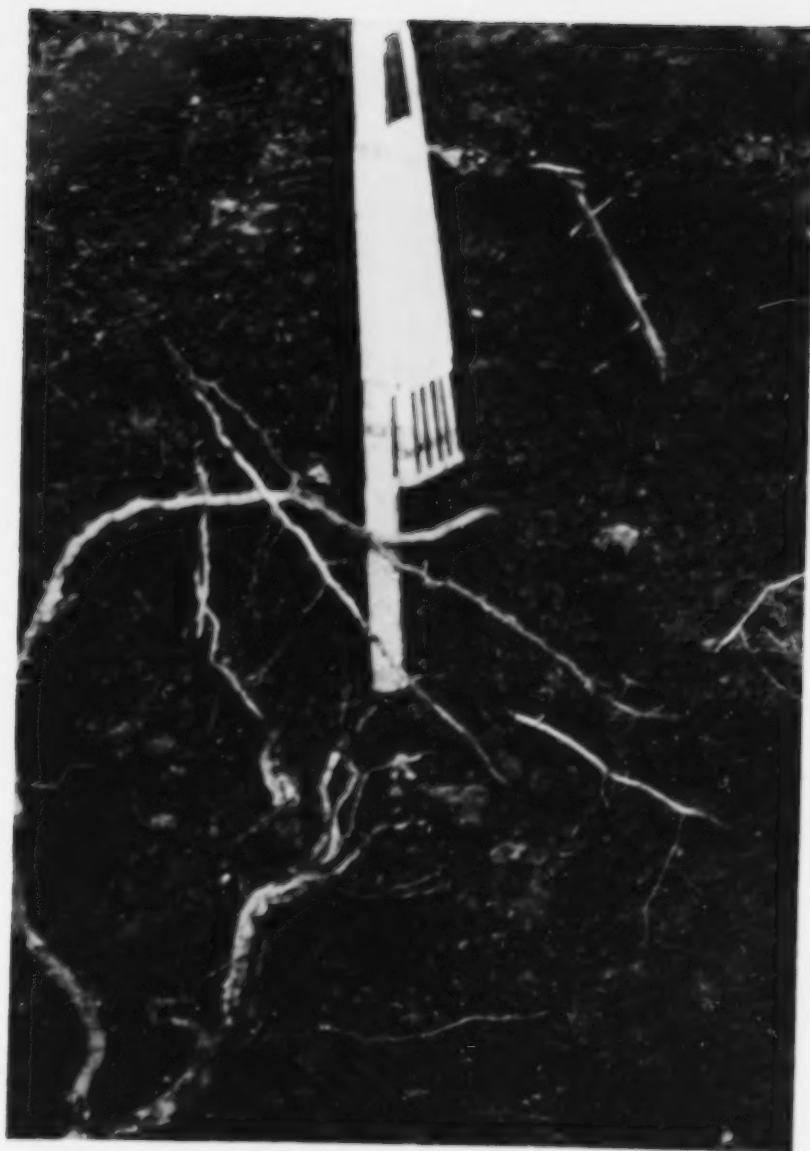


Figure 45. Root system of hybrid poplar sapling A on control plot.

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TABLE 50. NUMBER OF 30.5-cm (12-IN) HYBRID POPLAR (SAPLINGS) ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH, TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄ AND O₂ CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

		Landfill				Control			
		Tree A (low)		Tree B (high)		Tree A		Tree B	
Soil depth in cm		# of root sections	gas %	# of root sections	gas %	# of root sections	%	# of root sections	%
0.5	1.3	11	6.4b ⁺	0	0c	5	1.3a	0	0a
1	2.5	40	23.1	13	20.6	42	10.6	44	18.2
2	5.1	39	22.5	20	31.7	68	17.1	30	12.3
3	7.6	24	13.9	10	15.9	55	13.8	27	11.1
4	10.1	12	6.9	2	3.2	27	6.8	23	9.5
5	12.7	10	5.8	1	1.6	27	6.8	26	10.7
6	15.2	9	5.2	5	7.9	32	8.1	27	11.1
7	27.9	13	7.5	7	11.1	32	8.1	25	10.3
8	20.3	9	5.2	4	6.4	44	11.1	18	7.4
9	22.8	2	1.1	1	1.6	30	7.6	5	2.1
10	25.4	1	0.6	0	0	14	3.7	6	2.5
11	27.9	0	0	0	0	6	1.5	3	1.2
12	30.5	0	0	0	0	0	0	1	0.4
13	33.0	1	0.6	0	0	0	0.2	2	0.8
14	35.6	0	0	0	0	3	0.7	2	0.8
15	38.1	1	0.6	0	0	3	0.7	2	0.8
16	40.6	0	0	0	0	1	0.2	1	0.4
17	43.2	0	0	0	0	0	0	0	0
18	45.7	1	0.6	0	0	0	0	0	0
19	48.3	0	0	0	0	2	0.5	1	0.4
20	50.8	0	0	0	0	2	0.5	0	0
21	53.3	0	0	0	0	1	0.2	0	0
						2	0.5	0	0
Total length (m)		52.7		19.2		121.0		74.0	
Mean depth (cm)		8.4		8.6		12.5		13.2	
Maximum depth (cm)		45.7		22.8		53.3		45.7	
CO ₂		1.2		7.9		1.2		1.2	
O ₂		19.1		17.1		19.1		19.1	
CH ₄		0.0		1.8		0.0		0.0	

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

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TABLE 51. NUMBER OF 30.5-cm (12-IN) HONEY LOCUST ROOT SECTIONS AND PERCENTAGE TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄ AND O₂ CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS⁴

Soil depth in cm	Landfill				Control			
	Tree A		Tree B		Tree A		Tree B	
	# of roots	%	# of roots	%	# of roots	%	# of roots	%
1 2.5	3	6.7a ⁺	2	3.0a	0	0b	0	0b
2 5.1	24	53.3	40	60.6	29	16.3	33	19.4
3 7.6	4	8.9	11	16.7	16	9.1	9	5.3
4 10.1	6	13.4	5	7.6	7	3.9	9	5.3
5 12.7	3	6.7	0	0	6	3.4	33	19.4
6 15.2	1	2.2	0	0	11	6.2	17	10.0
7 17.8	0	0	5	7.6	18	10.1	9	5.3
8 20.3	2	4.4	1	1.5	38	21.3	17	10.0
9 22.8	1	2.2	1	1.5	8	4.5	14	8.2
10 25.4	1	2.2	0	0	16	9.1	12	7.1
11 27.9	0	0	0	0	19	10.7	5	2.9
12 30.5	0	0	1	1.5	9	5.1	6	3.5
13 33.0	0	0	0	0	0	0	3	1.8
14 >33.0	0	0	0	0	1	0.6	2	1.2
Total length (m)	13.7		20.1		54.2		51.8	
Mean depth (cm)	8.9		7.6		17.5		15.7	
Maximum depth (cm)	25.4		20.5		35.6		48.2	
CO ₂	5.1		5.9		0.9		1.3	
O ₂	16.1		17.5		18.7		19.1	
CH ₄	1.6		1.8		0.0		0.0	

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

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Figure 46. Diagram of honey locust tree B root system on landfill plot indicating root depth at 30.5-cm (12-in) intervals.

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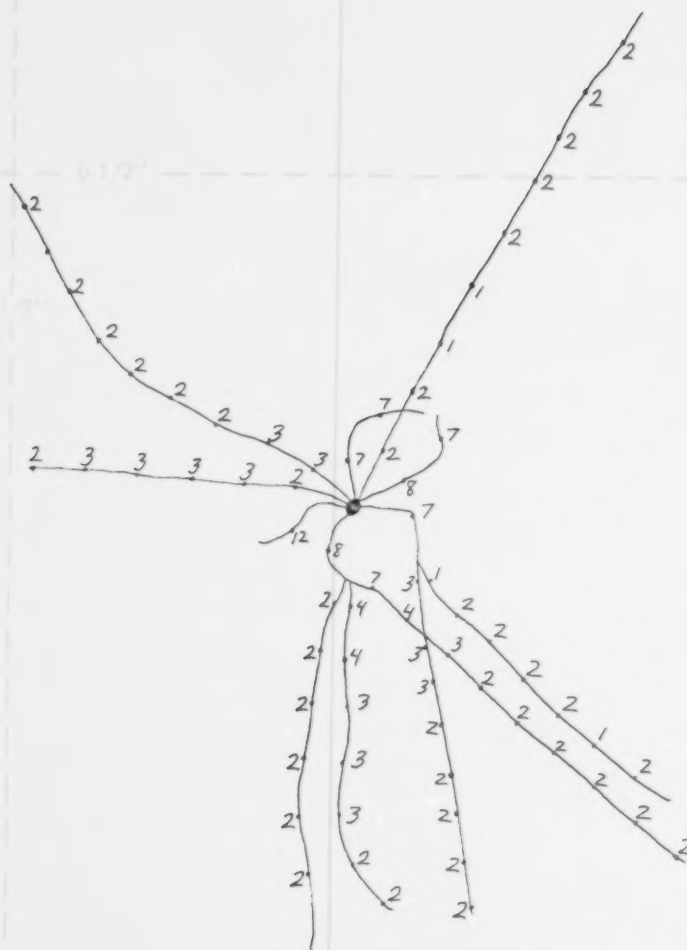


Figure 47. Diagram of honey locust tree A root system on landfill plot indicating root depth at 30.5-cm (12-in) intervals.

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Figure 48. Root system of honey locust tree A on landfill plot.

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toward the soil surface as they grew away from the trunk (Figures 49 and 50). Several roots such as those indicated with arrows in Figure 51B, grew away from the soil surface. However; control locust roots generally remained at the same soil depth throughout their entire length (Figure 51B). Many roots were found at depths between 10 cm (4 in) and 25 cm (10 in) (Figure 51A). The arrow above the hand shovel shows the approximate location of the soil surface. The root at the tip of the shovel was approximately 25 cm (10 in) deep.

Two Japanese black pine trees were excavated on the landfill and control plots. Carbon dioxide (5.6%) and methane (1.1%) concentrations were higher and oxygen (18.3%) concentrations lower on the landfill than on the control plot ($\text{CO}_2=1.2\%$, $\text{CH}_4=0.0\%$, $\text{O}_2=19.8$) (Table 52). Root distribution on the landfill plot (Figures 52 and 53) was statistically similar to that in the control plot (Figures 54 and 55). Total root length and mean root depth values on the landfill were similar to those on the control (Table 52). Maximum root depth was slightly greater on the control than on the landfill plot.

Two Norway spruce trees were excavated on the landfill and control plots. Carbon dioxide (4.7%) and methane (0.6%) concentrations were higher and oxygen concentrations were lower (18.4%) on the landfill than on the control ($\text{CO}_2=1.2\%$, $\text{CH}_4=0.0\%$, $\text{O}_2=19.8\%$) (Table 53). Roots of Norway spruce tree A were concentrated very close to the soil surface (Table 53); whereas, roots from tree B were growing in deeper soil layers. The same pattern was observed on the control plot, where one tree A produced a very shallow root system, whereas, the other tree B had many roots in deeper soil layers. Roots on both plots grew very straight and rarely branched (Figures 56, 57, 58, 59). Figure 60 illustrates the shallow root system of the Norway spruce on the landfill plot and Figure 61 demonstrates the shallow roots on the control.

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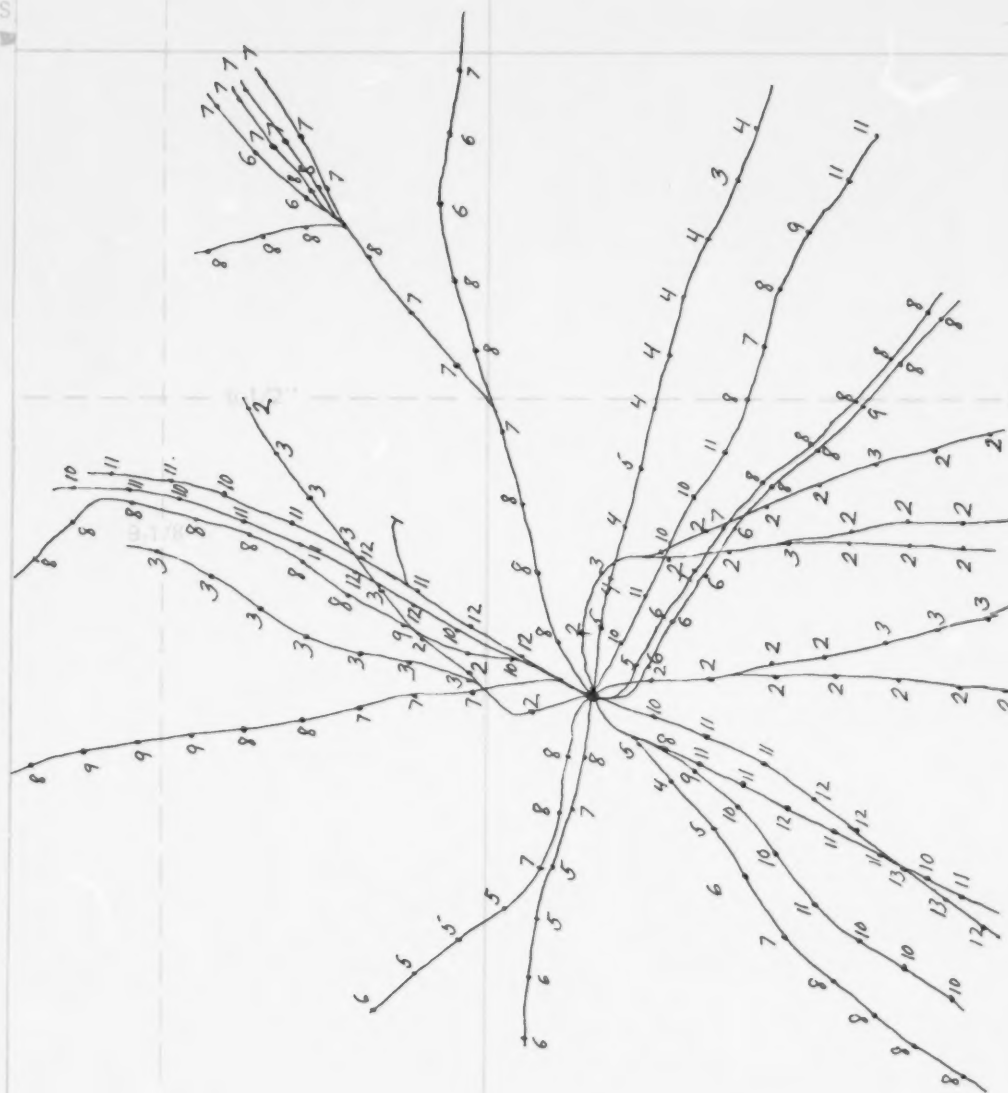


Figure 49. Diagram of honey locust tree A root system on control plot indicating root depth at 30.5-cm (12-in) intervals.

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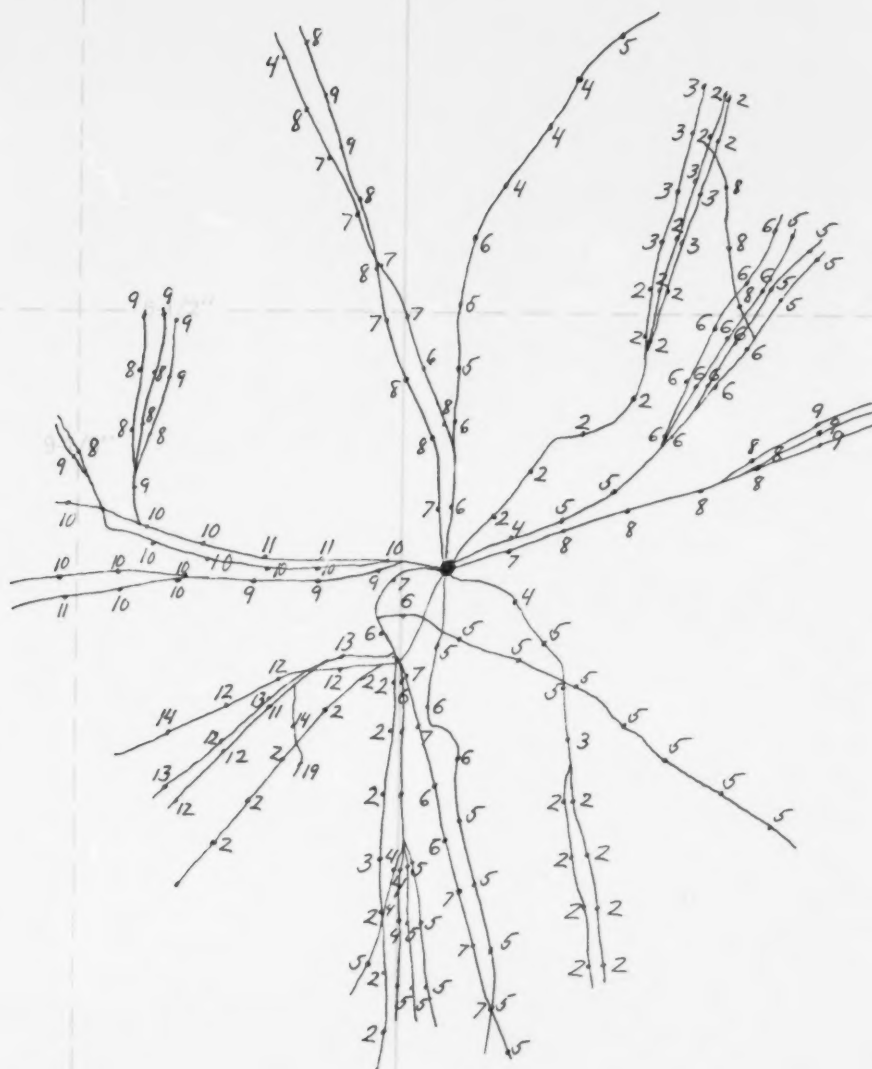


Figure 50. Diagram of honey locust tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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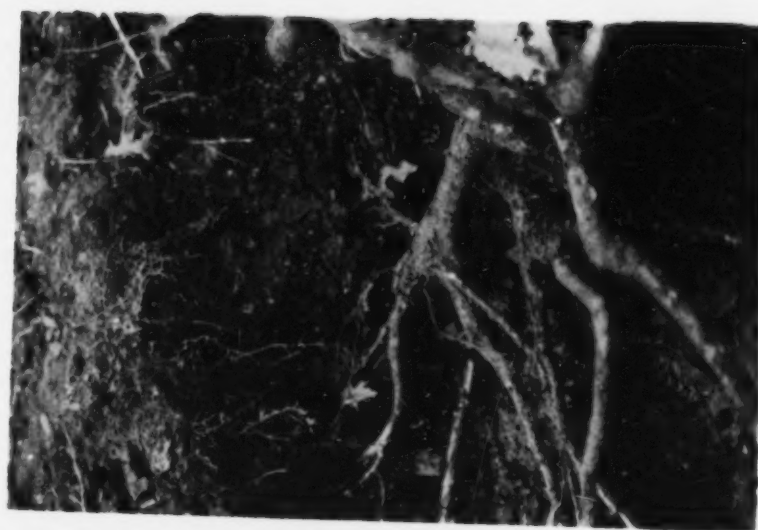


Figure 51. Root system of honey locust tree A on control plot.

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TABLE 52. NUMBER OF 30.5-cm (12-IN) JAPANESE BLACK PINE ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH, TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂, CH₄ AND O₂ CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

Soil depth in cm		Landfill				Control			
		Tree A		Tree B		Tree A		Tree B	
		# of roots	%	# of roots	%	# of roots	%	# of roots	%
1	2.5	0	0a ⁺	0	0a	0	0a	2	2.8a
2	5.1	39	56.5	43	46.7	24	30.4	28	38.9
3	7.6	13	18.8	17	18.5	21	26.6	25	34.6
4	10.1	7	10.1	16	17.4	8	10.0	6	8.3
5	12.7	4	5.8	9	9.8	4	5.1	4	5.6
6	15.2	4	5.8	5	5.4	7	8.9	2	2.8
7	17.8	1	1.5	2	2.2	4	5.1	2	2.8
8	20.3	1	1.5	0	0	8	8.9	1	1.4
9	22.8	0	0	0	0	2	2.5	2	2.8
10	25.4	0	0	0	0	2	2.5	0	0
Total length (m)		21.0		28.0		24.1		21.9	
Mean depth (cm)		7.6		8.1		10.4		8.1	
Maximum depth (cm)		20.3		17.8		25.4		22.8	
CO ₂		5.1		6.2		1.2		1.2	
O ₂		18.9		17.8		19.8		19.8	
CH ₄		1.4		0.9		0.0		0.0	

+ Columns with similar letters have similar root distributions at P<.01 by Chi-Square Analysis.

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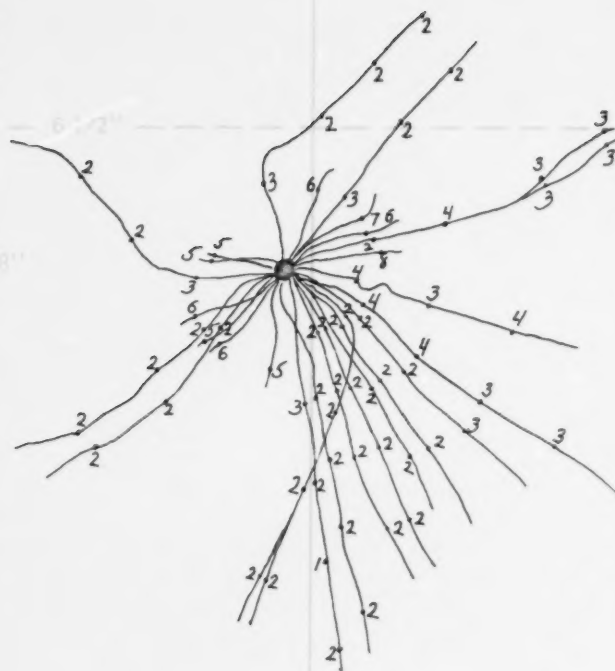


Figure 52. Diagram of Japanese black pine tree A root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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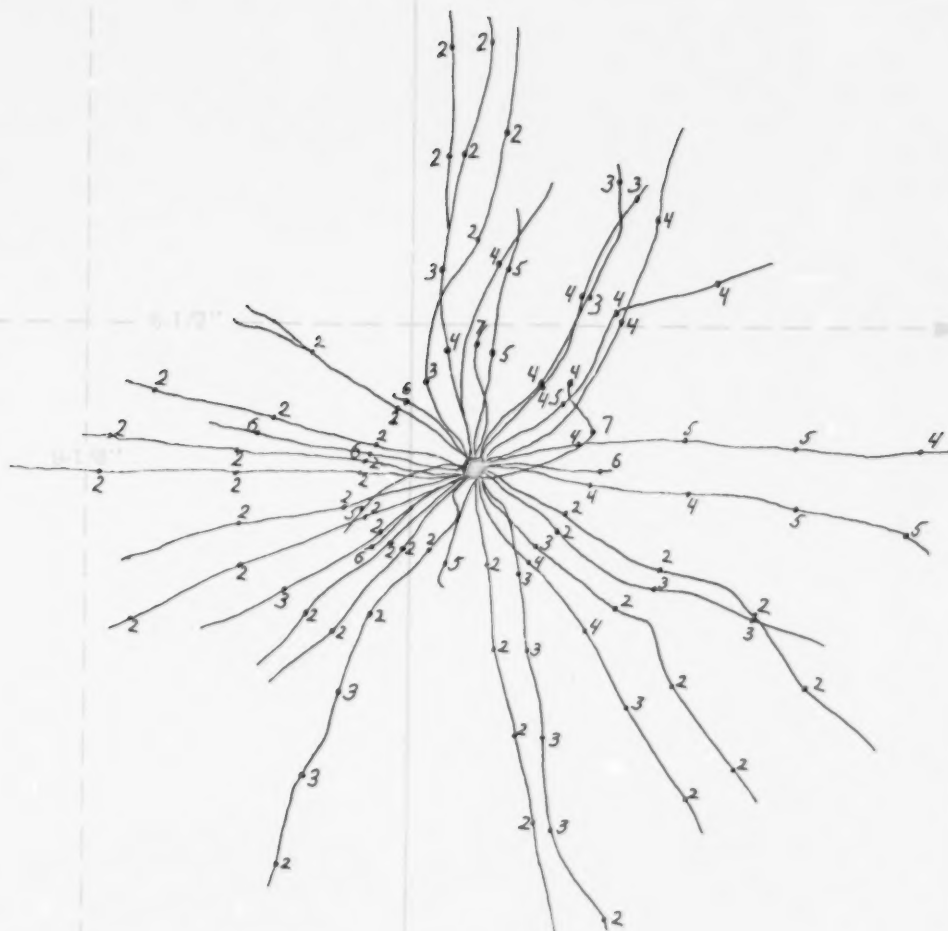


Figure 53. Diagram of Japanese black pine tree B root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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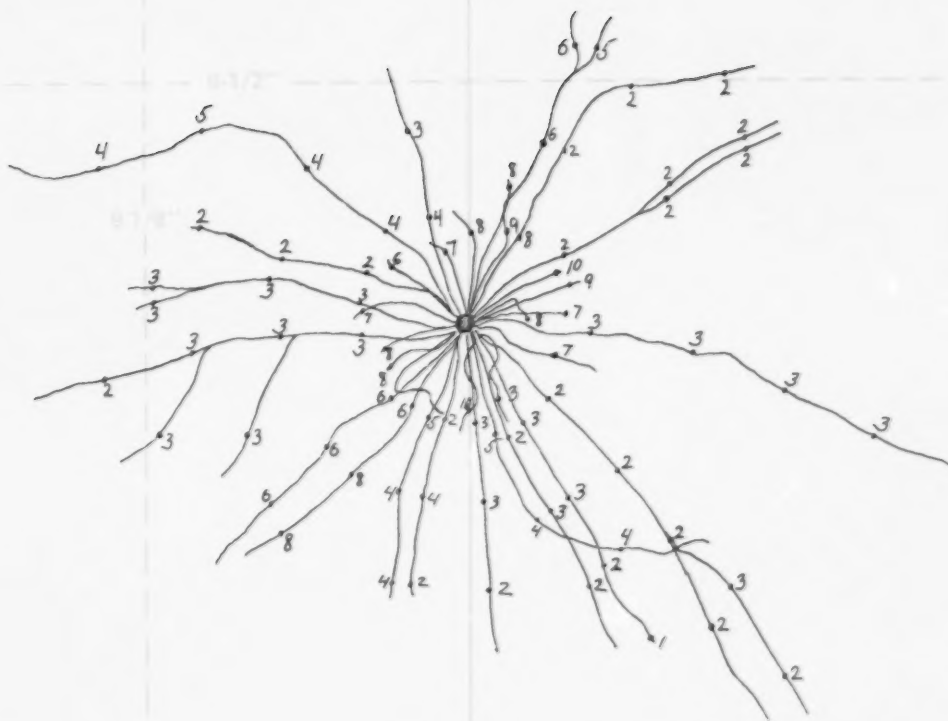


Figure 54. Diagram of Japanese black pine tree A root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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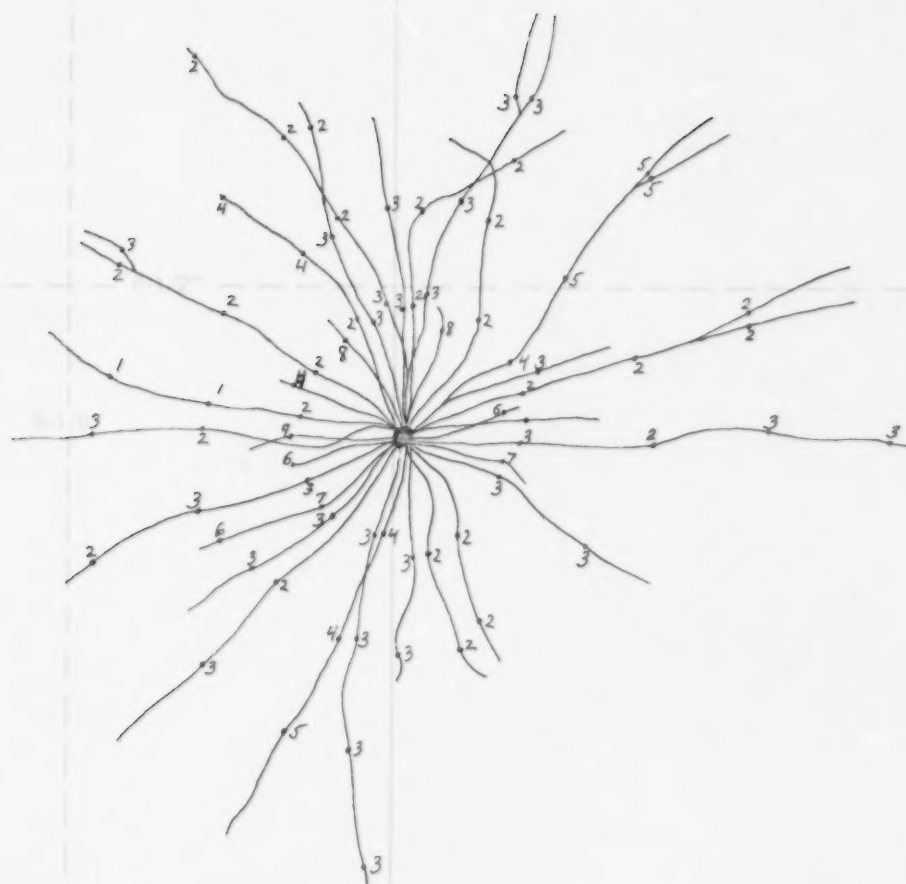


Figure 55. Diagram of Japanese black pine tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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TABLE 53. NUMBER OF 30.5-cm (12-IN) NORWAY SPRUCE ROOT SECTIONS AND PERCENTAGE OF TOTAL ROOT LENGTH AT EACH SOIL DEPTH; TOTAL ROOT LENGTH, MEAN ROOT DEPTH AND MAXIMUM ROOT DEPTH; CO₂ CH₄ AND O₂ CONCENTRATIONS ON LANDFILL AND CONTROL PLOTS

Soil depth in cm	Landfill				Control			
	Tree A		Tree B		Tree A		Tree B	
	# of roots	%	# of roots	%	# of roots	%	# of roots	%
1 2.5	99	83.2a ⁺	3	4.3c	92	86.0a	19	29.2b
2 5.1	18	15.1	26	38.8	12	11.2	24	36.9
3 7.6	2	0.7	25	36.2	3	2.8	14	21.5
4 10.1	0	0	12	17.4	0	0	6	9.2
5 12.7	0	0	3	4.3	0	0	1	1.6
6 15.2	0	0	0	0	0	0	0	0
7 17.8	0	0	0	0	0	0	1	1.6
Total length (m)	36.3		21.0		32.6		19.8	
Mean depth (cm)	3.0		7.1		3.0		5.4	
Maximum depth (cm)	7.6		12.7		7.6		17.8	
CO ₂	4.2		5.0		1.1		1.2	
O ₂	18.1		18.7		19.6		19.8	
CH ₄	1.1		0.2		0.0		0.0	

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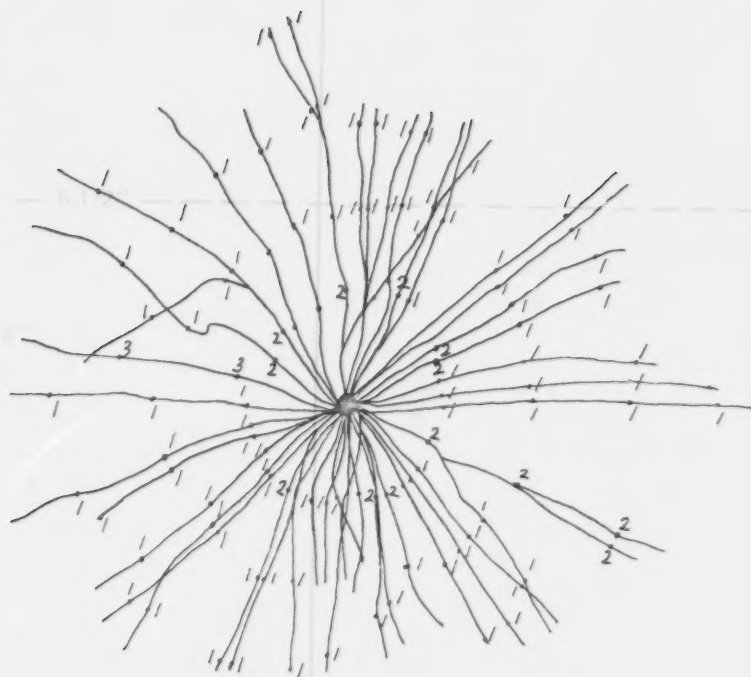


Figure 56. Diagram of Norway spruce tree A root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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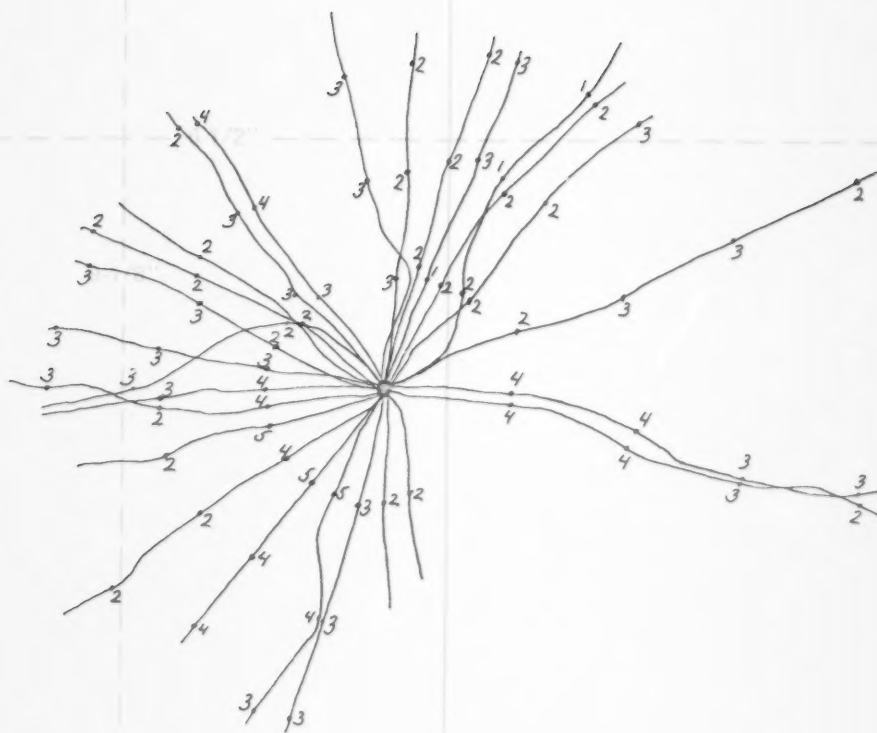


Figure 57. Diagram of Norway spruce tree B root system on landfill plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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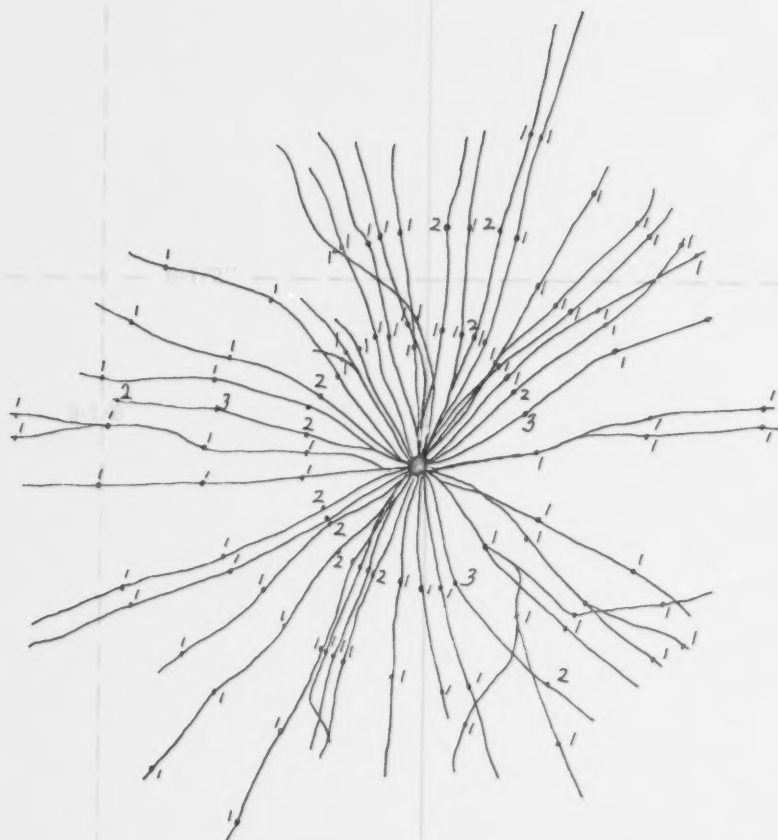


Figure 58. Diagram of Norway spruce tree A root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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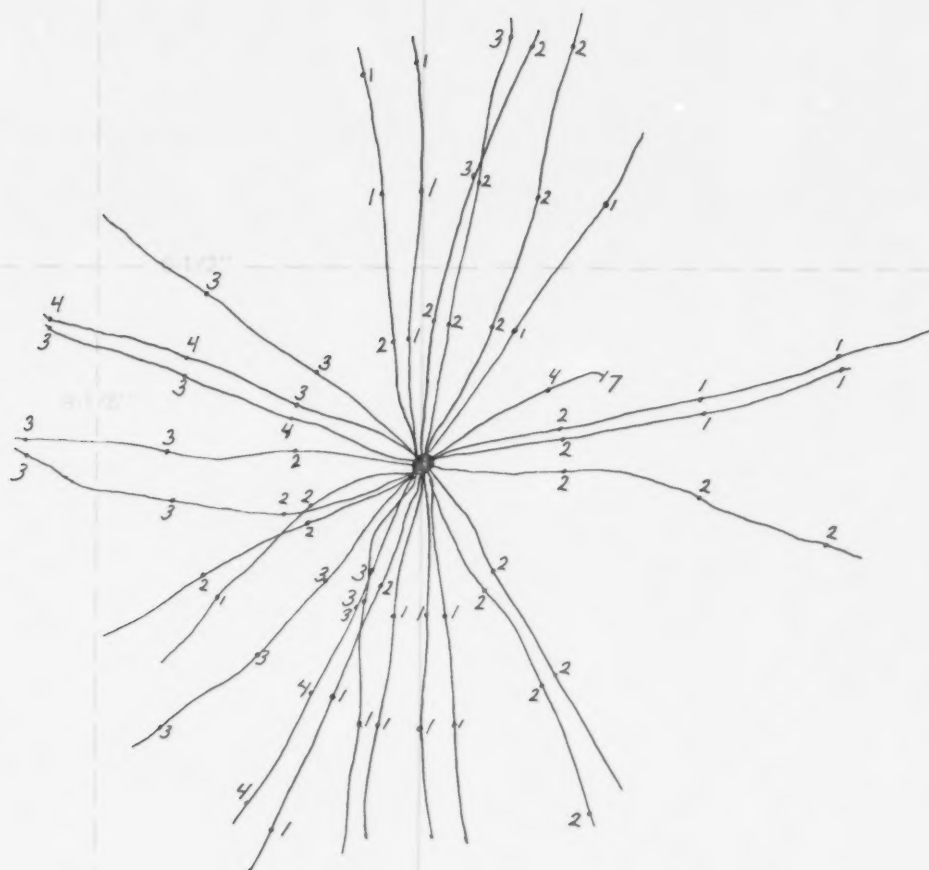


Figure 59. Diagram of Norway spruce tree B root system on control plot indicating root depth (in inches) at 30.5-cm (12-in) intervals.

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Figure 60. Root system of Norway spruce on landfill plot.

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Figure 61. Root system of Norway spruce on control plot.

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SECTION 7

DISCUSSION

The levels of carbon dioxide (3.9%), methane (0.4%) and oxygen (17.6%) at the 20 cm (8 in) depth in the cover soil of the Edgeboro landfill were found to be similar to levels found in the cover soil of over 67% of landfills surveyed throughout the United States (Leone et al, 1979). Therefore, the principles set forth in this report represent conditions indicative of a large number of landfills in this country.

Relative Viability of Plants

The viability of plants after four years growth on the completed Edgeboro landfill differed among species. By the end of 1979, all the weeping willows, rhododendrons, and euonymus had died on the landfill plot; willows and rhododendrons, obviously having been unable to withstand periods of desiccation characteristic of such sites during mid-summer. The euonymus shrubs on the site which were not girdled by rabbits during the winter of 1977-1978, also appeared to have become desiccated during mid-summer from lack of sufficient soil moisture. Several sweet gum, black gum, bayberry and pin oak died from undetermined causes; landfill gas contamination of the root zone and low soil moisture during mid-July 1978 were suspected as contributing factors in the sweet gum deaths. Since the concentrations of carbon dioxide, oxygen and methane at the 20 cm (8 in) soil depth can reportedly vary from one day to the next, some tree deaths may have resulted from landfill gas migrating into the root zone during periods when gas measurements were not determined; i.e. samples might have been collected on days of lower concentrations. If this were the case, harmful levels of the measured soil gases might not have been recorded. Even if the carbon dioxide and methane levels were considerably higher than the average levels during short intervals between sampling dates, Arthur (1978) indicates that short periods of high landfill gas concentrations may adversely affect tree growth.

More than 60 additional gases have been reported in the anaerobic environment of landfills (Personnel communication, Fred Rice, Reserve Synthetic Fuel, California, 1977) including ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxides (McCarty 1963; Rovers and Farquhar 1972; Toerian and Hattingh 1966). Some or all of these other gaseous components in addition to carbon dioxide and methane may have migrated into the cover soil in the landfill plot on the Edgeboro landfill and adversely affected plant growth.

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Relative Growth of Surviving Plants

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Landfill tolerance of the surviving trees was based upon two types of growth measurements (shoot length and stem area increase) taken for each species on both the landfill and control plots. From comparisons of growth on the landfill as percent of that on the control, relative tolerance of landfill conditions depended both on the growth parameter measured and the growing season in which measurements were collected. During the 1978 growing season, black pine shoot and stem growth on the landfill plot compared to the control was better than for any other species (Tables 4 and 5). During 1979, however, shoot growth of black pine on the landfill was fourth and stem growth tenth best of all species as compared to controls. Thus, black pine appeared to be less tolerant of landfill conditions in 1979 than in 1978. Honey locust shoot and stem growth on the landfill plot compared to the control during 1978 were fifteenth and sixteenth in rank, respectively among the species tested; whereas, during 1979, honey locust shoot growth was best and stem growth fifth best of all species tested. Evidently, a tolerance list based on growth measurements during one particular growing season may not necessarily represent a reliable estimate of an overall tolerance to landfill conditions. 6-1/2"

Since landfill tolerance also appears to be dependent upon the particular growth measurement in question, one must identify the critical growth criteria for species selection. Since either shoot growth and/or stem growth may be critical for a particular vegetation project, they have been presented in this report both separately and combined, in order to satisfy the needs of a wide variety of individuals.

From comparisons of total amount of shoot growth produced on the landfill from 1976 through 1979 with that in the control plot, ginkgo, black gum and Japanese yew appear to be most tolerant; and green ash, sweet gum and hybrid poplar saplings, least tolerant of landfill conditions (Table 8). From comparisons of percent stem area increase Japanese yew, white pine and Norway spruce seem most tolerant; and hybrid poplar cuttings, hybrid poplar saplings, and green ash, least tolerant of landfill conditions (Table 9).

Since there is reason to believe that no one growth parameter is best suited for comparing tree growth on the landfill with that on the control plot, shoot and stem growth data were combined for the years 1976, 1977, 1978 and 1979 and analyzed as a unit. Two different statistical methods were chosen to analyze the combined growth data in order to rank the test species for overall tolerance to landfill conditions.

One method consisted of averaging shoot growth during 1976 when stem growth was not available and shoot and stem growth for 1977 through 1979 for each species on the landfill plot as a percentage of that on the control plot. The species which produced the greatest amount of shoot or stem growth on the landfill compared to the control received a rank of one. The species which grew most poorly on the landfill compared to the control was ranked last (16th). Thus, seven rank lists were formed and the tolerance rank values from the lists were totaled for each species for an overall landfill tolerance rank (Table 10).

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Principal components analyses of shoot and stem data from 1976 through 1979 comprised the second method (Table 11). A factor score was calculated for each species on each plot. The differences in scores between plots were aligned from smallest to largest. The ranking of species from most to least landfill tolerance by this system was similar to the first analytical method. Only two species changed positions dramatically; Japanese yew moved from most tolerant by the first method to eighth according to principal components analysis, and hybrid poplar cuttings moved from eighth in tolerance by the first and least tolerant by the second analysis. As a result of both methods of analysis black gum, black pine and bayberry appeared most tolerant and hybrid poplar saplings, green ash and honey locust least tolerant of landfill conditions.

A final way of assessing relative tolerance to landfill conditions is to total the rank values from each of the aforementioned methods of analysis (Table 12). Black gum appears most tolerant and Japanese yew second most tolerant to landfill conditions. It is believed that Japanese yew was ranked very tolerant because growth on the control was inhibited by 'wet feet' conditions.

In all the landfill tolerance lists the species were generally distributed in a similar manner throughout tolerance ranks, i.e. those at the top of one list generally appeared toward the top of the other lists and vice versa.

Stress on the intolerant trees provided by low moisture and/or elevated CO₂ and CH₄ concentrations was reflected in the greater variability in growth on the landfill plot than on the control (Tables 13 and 14). Since tolerant species were apparently more capable than the intolerant species of withstanding the low soil moisture and elevated CO₂ and CH₄ levels of the landfill plot, the lower variability among tolerant trees on the landfill comes as no surprise.

From the previous discussion the following questions must be answered prior to the selection of plant material: Should it produce a quick vegetative cover? Must it grow in a manner similar to trees on non-landfill sites? Should it produce good shoot growth, good stem area increase or both?

Regardless of whether shoot length or stem area measurements are considered, rooted cuttings of hybrid poplar appear to be best suited for vegetating completed landfills if one desires to produce a quick, dense woody vegetative cover regardless of species (Table 15). On the other hand, if one desires to plant a variety of species which would perform as well on a landfill as on non-landfill areas, black gum, bayberry, Japanese black pine and ginkgo appear to be the tree species best suited for this purpose (Tables 10 and 11). Although two of these bayberry and ginkgo both ranked high in these species tolerance lists comparing their growth on the landfill with growth of replicates on the control, their relative absolute growth compared to that of other species on the landfill was the poorest.

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From this viewpoint, ginkgo might be one of the least desirable species for landfill plantings. Moreover, since bayberry was the only shrub to

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survive on the landfill plot and because it rapidly spreads by shallow horizontal rhizomes, bayberry may be a very desirable soil stablizer.

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Tolerance of Rapid vs. Slow Growers

Table 12 shows that seven of the eight most intolerant species (those toward the bottom of the list) have been classified as rapid growers; most of the tolerant species are slow growers (Fowells 1965). Apparently, those species with the capacity to grow very quickly, cannot maintain this rapid growth rate on completed landfills, whereas, species which naturally have a slower growth rate can maintain the rate on the landfill comparable to that on the control. Since fast growing trees are likely to withdraw more moisture from the soil, they may become subjected to water stress quicker than the slow growers. Localized low soil moisture tension zones may have existed in the rhizosphere of these rapidly growing trees; however, moisture content measurements were not taken on such a small scale. These data suggest that irrigation is more essential for the establishment of rapid growing trees than it is for establishment of the slow growers. Thus, when growth on the landfill was compared to growth on the control, rapidly growing trees proved intolerant of landfill conditions. However, many of these supposed intolerant (based on landfill growth compared to control) rapid growing species (hybrid poplar rooted cuttings, honey locust and American sycamore) actually produced more absolute vegetative growth on the landfill than other so called tolerant species growing on the landfill.

The generalization is often found in the literature that healthy, vigorously growing plants are susceptible to air pollution damage (Harkov 1979). Although slow growth may be associated with a given stress, it may also be characteristic of a particular plant species and thus allow that species to escape from air pollution damage (Harkov 1979). The present study presents evidence that trees more susceptible to landfill gases (pollution of the root system) are also more likely to be found among the rapidly growing species rather than the slower growers.

Tolerance of Flood Tolerant Species

The characteristic low moisture-holding capacity of landfill cover soils was demonstrated on the experimental landfill plot during the years 1977 and 1978 (Figure 7). Thus, several species may have been stressed by low available soil moisture. Species most likely to be affected by water stress are those which naturally grow in areas associated with a high water table. Five of the eight species (Green ash, honey locust, sweet gum, pin oak, red maple) observed to be landfill stressed in these investigations (Table 12), reportedly cannot tolerate drought conditions (Hook 1973), whereas, only one of the eight tolerant species is reportedly sensitive to droughty conditions. Several of these intolerant species (green ash, red maple, honey locust) may have exhibited sensitivity to landfill soil conditions because they cannot tolerate periods of low soil moisture content and might otherwise have proved to be landfill tolerant if adequate amounts of water had been provided.

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A reasonable a priori assumption may be that those species which can withstand periods of flooding, can also tolerate landfill conditions, since

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both environments generally lack sufficient oxygen for normal root respiration. However, since the soil on the Edgeboro Landfill was often lacking in moisture, these species were probably not afforded the opportunity to exhibit their low O₂-adaptability mechanisms. Thus, their growth on the landfill was much reduced compared to the control.

Effect of pH on Tolerance

There is evidence for the notion that soil pH levels may affect species tolerance to landfill conditions. During 1978, pH on both the landfill and control plots averaged 4.5. The tolerance (according to 1978 stem increment data) of the five most landfill tolerant species (black pine, Norway spruce, bayberry, white pine and black gum-Table 5) may have been brought about by the ability of these species to thrive in acidic soil (Flannery and Paterson 1964). Accordingly, these five species may have been less affected by the depressed O₂, elevated CO₂ and CH₄ and low soil moisture than other species because the pH (4.5) was close to their optimum requirement (pH=5.0-6.0). Following appropriate lime application in early spring, 1979, the soil pH rose to 6.2 on both plots, representing a much more desirable level for most trees and shrubs. As a consequence, the five low-pH species were no longer concentrated at the top of the landfill tolerance list on the basis of 1979 stem growth (Table 7). Species which were inhibited by low soil pH (e.g. red maple) in 1978, improved their growth on the landfill during 1979 when the pH level was not inhibiting and, therefore, moved up in the tolerance list, thus displacing several of the more acid loving plants like Japanese black pine.

Although stem area increase data provide evidence for the importance of soil pH on landfill tolerance, shoot length data exhibits no recognizable relationship between the two parameters. This indicates that stem area increase may be a more sensitive indicator for the tolerance of woody species to landfill conditions than is shoot length.

Effect of Soil Compaction on Tolerance

High soil bulk density is another factor which may have influenced the response of a number of the test species to the soil environment created on the landfill plot. Hopkins and Patrick (1969) indicate that plants are more adversely affected by high soil bulk densities at depressed soil oxygen levels (<10%) than at normal soil oxygen concentrations (18-20%). Gilman et al, (in press) report that growth of American basswood on completed sanitary landfills is significantly inhibited at high soil bulk density levels. Optimum levels of soil bulk density for a variety of crops vary between 1.3-1.5 g/cc. Since bulk density on the landfill plot during the current investigations was 1.8 g/cc, the lowered oxygen content in the landfill soil may have caused some species to be affected by high soil compaction.

Tolerance of Shallow vs. Deep-Rooted Species

The species which adapted to the landfill plot more quickly (Japanese black pine, Norway spruce) have a shallower and more extensive root system on the landfill than the intolerant species (honey locust, green ash, hybrid

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poplar) (Table 43). All species produced a shallower root system on the landfill than on the control except Norway spruce. However, the difference in root depth between landfill and control plots was small for black pine and spruce compared to a fairly large difference for the intolerant because they had to produce a proportionally shallower root system on the landfill than on the control than did the tolerant species. This study presents evidence that the root systems of these presently intolerant species are making their way toward the soil surface and may in several years be able to tolerate landfill conditions. Their root system will probably have grown away from the higher carbon dioxide and methane concentrations (and consequently, lower oxygen concentrations) in the deeper soil strata, and will probably require extensive irrigation in order to maintain growth comparable to the control.

Tolerance of Small vs. Large Trees

The enhanced landfill adaptive capabilities of small trees compared to large trees appears to be supported by evidence presented in this report wherein shoot growth for small trees of four (pin oak, green ash, sugar maple, hybrid poplar) of five species tested was equally good on the landfill as on the control, whereas, shoot growth on the large specimens (saplings) was significantly lower ($P < .10$) on the landfill than on the control plot.

Tolerance of Balled-and-Burlapped vs. Bare-rooted Material

Another practice involving root characteristics which may aid trees in becoming adapted to stressed environments is the use of balled-and-burlapped material rather than bare-rooted stock. In this investigation with a single species, sugar maple, balled-and-burlapped trees produced longer shoots and greater leaf volume than bare-rooted trees on the landfill plot, but not on the control plot. Obviously there was some advantage in having a less pruned root stock. There may also have been better mycorrhizae inoculum in the soil ball. However, whether this is a characteristic of one species or whether the results may be extrapolated to other species must be further determined by further experiments.

Tolerance of Irrigated vs. Non-irrigated Plants

Sugar maple was used to assess the value of supplemental irrigation in adapting trees to landfill cover soils. This species generally grew better in the control soil having higher moisture and oxygen contents and lower carbon dioxide than in the landfill. Although supplemental irrigation increased the soil moisture in both plots, irrigated maples produced significantly more ($P < .01$) leaf tissue than non-irrigated trees on the landfill but not on the control during 1978 and 1979. Shoot length was enhanced by irrigation in both plots, but the increase was not statistically significant. Possibly, the failure of irrigation in the control plot to stimulate growth was due to the fact that sufficient rain had fallen during the growing season so that moisture was not a limiting factor for growth of sugar maple on the control as it was on the landfill.

Decreased growth of sugar maples on the landfill plot was undoubtedly due

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to the combined effects of low soil moisture and slightly elevated soil carbon dioxide and depressed oxygen concentration. Also, the elevated carbon dioxide levels may have caused the production of a shallower root system on the landfill than on the control and, therefore, predispose the maples to drought damage. Gingrich and Russell (1957) report that oxygen and moisture content interact such that at high oxygen concentrations, low moisture content has a more deleterious effect on corn growth than at low oxygen contents. The oxygen concentration in the landfill soil was only slightly depressed, therefore, low soil moisture could have had a strong effect on maple development.

Arthur (1978) observed an increase in stomatal resistance, and hence reduced transpiration of sugar maples after several days of exposure to simulated landfill gas mixtures. A similar effect was observed in sugar maples growing in the landfill plot (Table 8). Elevated soil carbon dioxide concentrations (7.8%) in the non-irrigated portion of the landfill caused significantly increased stomatal resistance in the sugar maples from late morning until early evening (Figure 9) over that of the trees located on the landfill where carbon dioxide averaged 2.8%. Irrigation throughout the growing season did not significantly reduce the stomatal resistance below that of the non-irrigated area.

Air temperature, relative humidity, and other meteorological parameters are also known to affect stomatal aperture. Multiple regression analysis of diffusive resistance changes during the day showed that temperature and humidity effects accounted for 71% of the variability in the landfill irrigated area (equation 2-page 68) where the carbon dioxide (2.3%) and oxygen (17.9%) contents were close to that of non-landfill soils. Since only 16% and 0%, respectively, of the variability was explained by these two parameters in the non-irrigated areas with higher carbon dioxide and lower oxygen content the deleterious gas atmosphere and low moisture content of the soil appear to have prevented temperature and humidity from exhibiting an influence on stomatal resistance. Total wind movement from August 9 through August 23 alone accounted for 43% (equation 3) and 53% (equation 4) of the variability in stomatal resistance in the control irrigated and non-irrigated areas, respectively. After wind movement was entered into the equation, no other variable contributed significantly to the remaining variability. On the landfill plot, however, soil oxygen and moisture content contributed significantly to the variability. Apparently, the effects of adverse gas environment and reduced moisture content on stomatal aperture in the landfill plot have overridden the recognized effects of temperature, humidity and wind.

Effectiveness of Gas Barriers

Of the five landfill gas-barrier systems tested, the landfill mound lined with a 30 cm (12 in) clay layer appears to have promoted better growth of American basswood and Japanese yew than the unmodified landfill area. Basswood and yew with the unlined landfill mound was generally greater (but not significantly so) than in the unmodified landfill area (Table 22). In addition, the concentrations of carbon dioxide, methane and oxygen in the two landfill mounds were not significantly different from that in the unmodified control or control mound areas indicating that the mounding of soil functioned

successfully in preventing the upward migration of landfill decompositional gases into the root zone of gas susceptible plant species.

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Noticeable changes in soil nutrient contents were observed in areas with high landfill gas concentrations. Available soil manganese and iron contents during 1978 and 1979 were high in the clay/vents trench where the oxygen content was lowest (4.3%). Despite this relatively high average oxygen concentration, small pockets of anaerobic soil may have occurred in areas removed from the zone of influence around the gas samplers that may not have been measured. Leone et al. (1979) report that where the oxygen content in landfill soil averaged 4.3%, available manganese content was significantly higher ($P < .05$) than in other areas on the landfill where the oxygen concentration was 16.3% or higher. Data from the current study and the one cited above suggest that low oxygen levels in the landfill soils are associated with high levels of manganese. This is not surprising since high manganese and other micronutrient levels are frequently associated with flooded soils containing little or no oxygen (Ponnamperuma 1955).

An evaluation of the effects of varied soil environments on American basswood growth was made possible because of the variety of soil conditions found in the gas barrier and in other areas on the landfill and control plots. Correlation coefficients were calculated for a number of soil and tree parameters (Appendix B). Soil oxygen, carbon dioxide, potassium, manganese, nitrate content and bulk density were significantly correlated with all four growth parameters: shoot length, leaf weight, root biomass and stem increase. Multiple regression analyses were performed for the tree parameters using the soil gases, moisture content, bulk density, soil temperature and soil nutrient contents as independent variables. The models resulting from this analysis follow:

$$\text{Shoot length} = 0.41 + 0.10 (\text{Mn}^* - \text{Mn}^{**}) + 0.07 \text{NO}_3^{**}$$

$$R^2 = 55\% \text{ equation 4}$$

$$\text{Leaf weight} = 0.59 + 0.07 \text{NO}_3^{**} + 0.02 \text{Mn}^* + 0.01 (\text{K}^* - \text{K}^{**}) - 0.25$$

$$(\text{Bulk density} \times \text{Moisture content}). R^2 = 73\% \text{ equation 5}$$

$$\text{Root biomass} = 643.79 + 21.08 \text{NO}_3^{**} + 7.54 (\text{Moisture} \times \text{O}_2)$$

$$R^2 = 41\% \text{ equation 6}$$

Stem cross-

$$\text{section increase} = 23.51 + 0.55 \text{NO}_3^{**} + 0.71 (\text{Mn}^* - \text{Mn}^{**}) - 2.51$$

$$(\text{Bulk density} \times \text{Moisture content}). R^2 = 69\% \text{ equation 7}$$

These models suggest that soil nitrate and manganese levels had a direct effect on growth of the basswood trees.

Carbon dioxide and oxygen levels were also significantly correlated with

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*Indicates soil measurement in June 1977.

**Indicates soil measurement in October 1977.

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the four growth parameters; however, the correlation coefficients were slightly higher for the soil nutrients; hence, their inclusion in the regression models. The exclusion of the toxic soil gas (CO_2) from the models above does not suggest that they did not directly affect growth. Soil gases at these concentrations have been shown to dramatically affect vegetative growth (Flower et al 1978, Leone et al 1979). However, the high correlations between soil oxygen and soil nitrate levels ($r = + 0.63$) and between soil oxygen and soil manganese levels ($r = -0.80$) suggest that the oxygen concentration has dramatically affected the levels of nitrate and manganese in the soil. Although the data are not necessarily conclusive, we can state, as did previous investigators, (Hoeks 1972), that the presence of methane gas in soils is probably associated with microbial activity through which some plant nutrients, particularly nitrogen compounds and trace metals are made available. It is within the realm of possibility that some trace element (possibly manganese or iron), essential to plants at low concentrations, could be reaching toxic levels in soils contaminated by methane.

A reason for the absence of a soil moisture component in the equations describing shoot length variation may be that the basswoods concluded most of their shoot growth by early June, whereas, soil moisture was considered adequate or non-limiting for shoot growth until mid-June. On the other hand, the leaves continued to expand through early July and thus lack of soil moisture was able to exhibit an effect on leaf weight resulting in the inclusion of moisture content in the equation (eq. 5) explaining variability in leaf-weight.

The effects of soil moisture on stem and leaf growth depended on the soil bulk density level as shown by the cross-product term (bulk density X moisture content) in both models (eq. 5 and 7). For instance, at a high bulk density (1.8 g/cc), the higher soil moisture in the unmodified control area compared to the unmodified landfill area (Table 27), resulted in a significant increase in stem growth in the control (Table 24). On the other hand, at a medium bulk density (1.6 g/cc), the significantly higher soil moisture in the control trench compared to the clay trench, resulted in a non-significant increase in stem growth. Furthermore, at the low bulk densities (1.3 g/cc) found in the clay/vents and gravel trenches, a higher soil moisture content is associated with the poorest stem and leaf growth indicating the possibility that increasing soil moisture at low bulk densities may be detrimental to plant growth. More likely, low oxygen and/or high carbon dioxide contents inhibited growth in the clay/vents trench.

Soil oxygen and carbon dioxide are both significantly correlated with basswood growth (Appendix C) and both can reportedly cause a large effect on plant productivity (Leone et al 1979). Possibly, the high carbon dioxide and low oxygen concentrations in the clay/vents trench have affected basswood growth so that less water was removed from the soil by the trees in this area. Water is also a product of refuse degradation (Farquhar and Rovers 1972) and may travel through the soil along with the gases produced during decomposition. Thus, the higher soil moisture in the clay/vents trench appears to be a result of rather than a cause of poor growth. Therefore, the significance of the bulk density X moisture content term in the two models appears to depend solely on the high soil moisture in the clay/vents trench

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associated with very poor basswood growth.

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In order to evaluate the effect of the landfill environment on the total amount of nutrients accumulated by the basswoods in each test area, average weight of leaves per branch was multiplied by tissue nutrient concentration. The differences in total uptake among the nine areas were analyzed in two ways: first by using the total nutrient content and second by adjusting the nutrient means for bulk density and root biomass differences between areas.

Soil bulk density differences between areas resulted from differential soil compaction caused by the use of heavy equipment necessary in preparing the site for planting, therefore, neither the refuse, nor any products from it, had any influence on bulk density. Considering this and the correlation between bulk density and nutrient uptake, removal of the effect of bulk density on nutrient uptake allows for a better appraisal of the effects of landfill-influenced soil conditions on nutrient uptake. Root biomass differences between areas were influenced by landfill conditions (Gilman 1978). High positive correlations existed between basswood root biomass (even though it was measured quite crudely and varied considerably within each area) and total uptake of all eight nutrients measured. When the effect of root biomass on nutrient uptake was removed from the analysis by Analysis of Covariance, a measure of the efficiency of uptake at the root surface was obtained. This efficiency is an evaluation of the ability of a given section of root surface to absorb nutrients, regardless of the total amount of root surface available for absorption.

The most striking difference between the unadjusted (raw data) and adjusted means (efficiency after removal of bulk density and root biomass component for nutrient uptake per branch) is that after adjusting, nutrient accumulation in the gravel/plastic/vents trench and clay mound was no longer significantly greater than that in the unmodified experimental screening area, indicating that root biomass and bulk density had a great influence on nutrient accumulation. Consequently, basswoods in both landfill mounds, the gravel trench and the clay trench accumulated the eight nutrients no more efficiently than in the landfill screening area. In the clay/vents trench, nutrient uptake efficiency was actually significantly reduced. The carbon dioxide and methane gas concentrations were significantly greater ($P < .01$) and oxygen significantly lower in this area than in all other areas. Apparently, soil carbon dioxide can reach 7% and oxygen can drop to 16.3% with no effect on nutrient uptake efficiency. However, when the carbon dioxide concentration reached 22.8% and oxygen, 4.3% (clay/vents trench), nutrient accumulation efficiency was significantly reduced (Table 30).

Plants grown in soils low in oxygen often accumulate less potassium than those grown in soil with an adequate oxygen supply (Hammond 1955). If less potassium is taken up by the plant, then relatively more potassium should be left in the soil. This was true for American basswood in terms of concentration of potassium in the leaf tissue (Table 25) and total potassium uptake per branch (Table 26). More potassium was left in the soil (i.e. the potassium value in June minus that in October was small) in those areas where basswood leaf weight and total potassium uptake were low. This is represented in equation 2 by a positive coefficient for the potassium in June minus

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potassium in October effect in the model describing leaf weight variability. The oxygen concentration in two of these poor growth areas (clay/vents and clay trenches) was lower than in any of the other areas. Apparently the low oxygen, and/or high carbon dioxide, contributed somewhat to the low potassium uptake of the basswood growing in these trenches, resulting in the small change in soil potassium from June to October.

Foliar concentrations of manganese, nitrogen and potassium were significantly reduced ($P < .05$) in basswood trees growing in the area of highest carbon dioxide and lowest oxygen concentration (clay/vents trench). Similar phenomena were observed by Leyshan and Sheard (1974), i.e. concentrations of nitrogen, phosphorus and potassium were reduced in barley tissue grown in oxygen-deficient soils. Concentrations of nitrogen and potassium were also reduced in avocado (Labanauskas et al. 1968) and potassium was reduced in slash pine (Shoulders and Ralston 1975) when the plants were subjected to reduced oxygen concentrations.

Plants grown in sewage sludge treated soil where the available manganese is often quite high (e.g. 141 ppm) contain significantly higher concentrations of manganese relative to plants grown in non-sewage sludge treated soil. Since literature concerning the effects of low oxygen combined with high soil manganese on accumulation of manganese in tree tissue is wanting, interpretation of the decreased manganese concentration in basswood leaf tissue is at best, speculative. At first glance, lack of oxygen in the soil, causing disruption in respiratory activity in the root system and impairing manganese uptake appears to be an attractive explanation since oxygen level was positively correlated ($P < .05$) with tissue manganese content. However, concomitant with low soil oxygen are high carbon dioxide content, high temperature and on several occasions high methane and possibly other gases in lesser amounts such as hydrogen sulfide (H_2S). Hydrogen sulfide was not measured in the present study; however, detrimental effects of H_2S on root formation and activity have been reported (Hollis 1967, Hollis et al. 1975). Several authors working with the mechanisms of toxicity have indicated that the presence of H_2S may limit nutrient uptake (Joshi et al. 1975, Ponnampetuma 1975). There have been no reports of the effects of temperature or methane on nutrient uptake.

Tissue calcium concentration was significantly lower for the two areas (clay/vents and clay trenches) where oxygen was lowest and carbon dioxide highest in content. Soil temperature was also higher in the clay/vents trench than in all other areas. Regression analysis showed that the temperature during the growing season was highly correlated ($R^2 = +78\%$) with calcium concentration (Appendix C). These results are supported by Burstrom (1956) and Neilson (1971) who separately found that the soil calcium level required to maintain good wheat growth increased with increasing soil temperature from $20^\circ C$ to $30^\circ C$. When corn roots were exposed to cyclic temperatures, they reacted almost identically to the response corresponding to the maximum temperature alone (Rattan 1974). Consequently the correlation between some aspects of growth (i.e. calcium, copper and iron leaf tissue concentration) and highest temperature is not surprising.

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Only one of the nutrient elements measured, iron was more concentrated

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in the clay/vents trench than in any other area ($P < .05$). This area contained the lowest oxygen concentration (4.3%) throughout the entire growing season. It is reported that prolonged low oxygen concentrations brought about by flooded soil reduce iron making it more available to plants (Ponnamperuma 1955) and perhaps causing it to reach toxic levels (Ponnamperuma 1955). Low oxygen alone or in conjunction with flooded soil has also been associated with an increase in iron content in avacodo seedlings (Labanauski 1968). Whether or not iron was taken up by the basswood trees in quantities large enough to cause a toxic response is not determinable from the present study. These data suggest that landfill gases are at least partially responsible for influencing the total productivity and depth of penetration of the American basswood root system and are in agreement with previous work (Gilman 1978) which suggests that high gas concentrations are partially responsible for a decrease in root biomass of trees growing on landfills.

Root Growth in Landfill Cover Soil

Table 43 shows that although total root length and maximum penetration depth were decreased by landfill gases in the unmodified landfill and clay/vents trench areas; average root depth was apparently not reduced in the clay/vents trench where the gases reached their highest levels (22.8% CO_2 , 12.0% CH_4), but significantly reduced in the non-trench landfill area where the gas concentration was second highest (8.1% CO_2 , 5.8% CH_4). This apparent incongruity can perhaps be explained by the limited root growth in the clay/vents trench, i.e. roots may not have had enough time to grow toward the soil surface before the trees died and thereby avoid the high landfill gases due to the inhibition of growth by the gases or other soil factors early in the growing season.

Carbon dioxide concentration was significantly higher at the 20 cm soil depth in the un-modified landfill area than in any other area except the clay/vents trench. The majority (66.7%) of the roots in the non-trench landfill area extended toward the surface and proliferated there, resulting in the shallowest ($P < .05$) average root depth (7.4 cm) of all areas. It is believed that with the high landfill gas content of the clay/vents trench at the 20 cm soil depth, (22.8% CO_2 , 12.0% CH_4) and/or low oxygen content (4.3%), roots cannot grow to avoid this gas environment, but when the conditions are less severe, i.e. the unmodified landfill area (8.1% CO_2 , 0.9% CH_4 and 18.5% O_2), American basswood is capable of extending all of its root system 15.3 cm into the soil. Where the gas content at 20 cm was 1.0% CO_2 , 0.0% CH_4 and 19.5% O_2 , average root depth was 24.4 cm. Results for basswood (Gilman 1978) corroborate those for Japanese black pine, Norway spruce, hybrid poplar, honey locust and green ash discussed previously.

In order to further investigate the effects of high and low landfill gas (CO_2 and CH_4) concentrations on vertical root distribution in landfill cover soil, seedlings and saplings of hybrid poplar and green ash (one replicate of each from a relatively high-gas area and one from a relatively low-gas area on the landfill) were excavated and mapped. Two replicates of each were also excavated on the control for comparison (for a total of eight trees on each plot). Root distribution was significantly shallower ($P < .05$) in the high-gas areas than in the low-gas landfill areas for both seedlings and saplings of

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these two species. All landfill trees of both species had significantly ($P < .05$) shallower root systems than trees growing in the control plot.

The two factors which differed most between plots were soil gas concentrations and soil moisture content. Carbon dioxide, methane and oxygen concentrations at the 20 cm depth on the landfill ($\text{CO}_2=3.9\%$, $\text{CH}_4=0.4\%$, $\text{O}_2=17.6\%$) were significantly different ($P < .01$) than on the control ($\text{CO}_2=1.0\%$, $\text{CH}_4=0.0\%$, $\text{O}_2=19.9\%$). Soil moisture content averaged 9.0% on the landfill and 11.5% on the control. Since areas on the landfill plot where trees were excavated differed in gas concentration but were similar in moisture content, the shallower root system in the high-gas areas probably resulted from the difference in gas concentration rather than in moisture content. However, differences in root depth between landfill trees and the control trees could have resulted from landfill gas contamination and/or lower soil moisture levels on the landfill than on the control. Few landfill cover soil environments are characterized by low soil moisture content alone (Flower et al); most are associated with elevated levels of carbon dioxide and methane, depressed oxygen concentration, low soil moisture and a variety of other undesirable qualities.

Evidence has also been produced by these studies to suggest that species with a natural propensity toward producing shallow root systems (Japanese black pine, Norway spruce) (mean depth approximately 9 cm and 4 cm respectively on control plot) grew very well in landfill cover soil. Deeper rooted species (green ash, honey locust-mean root depth on control 14.7 and 16 cm respectively) were forced to respond to the landfill stresses through development of surface roots, when deeper roots are the norm and, therefore, grew less vigorously on the landfill than on the control plot.

Apparently, a desirable landfill species should have, in addition to low-oxygen tolerance, one of two rooting characteristics: either a naturally shallow root system or the ability to adapt from a characteristically deeper to a relatively shallower root distribution in order to avoid the deeper adverse soil gas atmosphere. Since only one (black gum) of the seven reportedly flood tolerant species (black gum, bayberry, American sycamore, red maple, green ash, honey locust, sweet gum) proved to be relatively tolerant of landfill conditions (Table 12), the respiratory mechanism responsible for allowing these species to survive in low oxygen environments, operating normally in a water-saturated environment, may not have functioned properly in the low moisture conditions of a landfill cover soil.

Gilman (1978) has previously reported that small trees may be more capable of adapting to landfill conditions than large specimens. In the current root distribution studies, roots of the hybrid poplar sapling (large tree) in the high-gas landfill area were unable to grow at the greater soil depths (30 cm). Only four roots remained alive at the time of excavation (October 1979) and these grew upward from approximately the 20 cm to the 5 cm soil depth. These roots appeared to have reached the soil surface very rapidly because the angle of the roots to the horizontal was rather steep compared to the angle for roots of the similar-sized poplars in the low-gas area. Many of the latter roots appeared to be growing toward the soil surface; whereas, few roots of the large poplars on the control plot grew from deeper to

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shallower soil depths, many roots actually grew deeper into the soil.

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The roots of hybrid poplar trees planted as cuttings (small trees) in the landfill soil also grew toward the soil surface; whereas, roots of small poplars on the control plot did not extend toward the soil surface. However, the rooted cuttings were planted with a very shallow root system, and, therefore, had to adapt less than the poplars planted as saplings which began with a much deeper root system and were more likely to encounter higher landfill gas concentrations than the more shallow roots of the poplar cuttings.

Unlike small-sized hybrid poplars, small green ash seedlings did not appear to adapt to landfill conditions to a better degree than larger specimens. Roots of both seedlings and saplings of this species appear to have adapted to the landfill soil conditions in a manner very different from hybrid poplar. Whereas, poplar roots originating at the deeper soil stratas on the landfill (20-30 cm) made their way upward as they elongated, the deeper green ash roots did not reach for the soil surface but, instead remained at the original depths where growth continued in a stunted fashion. Ash roots can reportedly tolerate low oxygen environments (Gill 1970). Ash roots in this study, therefore, have apparently tolerated adverse landfill gas concentrations ($\text{CO}_2=13.1\%$, $\text{CH}_4=7.3\%$, $\text{O}_2=12.3\%$). Even so, a large portion of the roots in the high-gas area sprouted from the root collar in the top 2.5 cm of soil (Figure 34), thus evincing a shallow root gas avoidance mechanism different from that of hybrid poplar.

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APPENDIX A

SHOOT AND STEM GROWTH RATES FOR EACH SPECIES ON LANDFILL AND CONTROL PLOTS

The graphs in this appendix represent shoot and stem growth rates for each species on the landfill and control plots. The species are arranged in descending order of relative tolerance to landfill conditions according to Table 12.

Legend

Shoot length = average shoot growth of all living replicates from 4 shoots per tree during 1976 (the longest shoot plus the 3 other longest shoots) and from 6 randomly selected shoots during 1977, 1978 and 1979.

Year = year during which measurement was collected.

Percent stem increase = percent stem cross sectional increase at heights above ground specified in Table 2 from March to October of the specified year.

Each species' graph can be found on the following pages:

Species	Page
Black gum	164
Japanese yew	166
Japanese black pine	168
Ginkgo	170
White pine	172
Bayberry	174
Norway spruce	176
American basswood	178
American sycamore	194
Red maple	192
Hybrid poplar rooted cuttings	190
Pin oak	188
Sweet gum	186
Honey locust	184
Green ash	182
Hybrid poplar saplings	180

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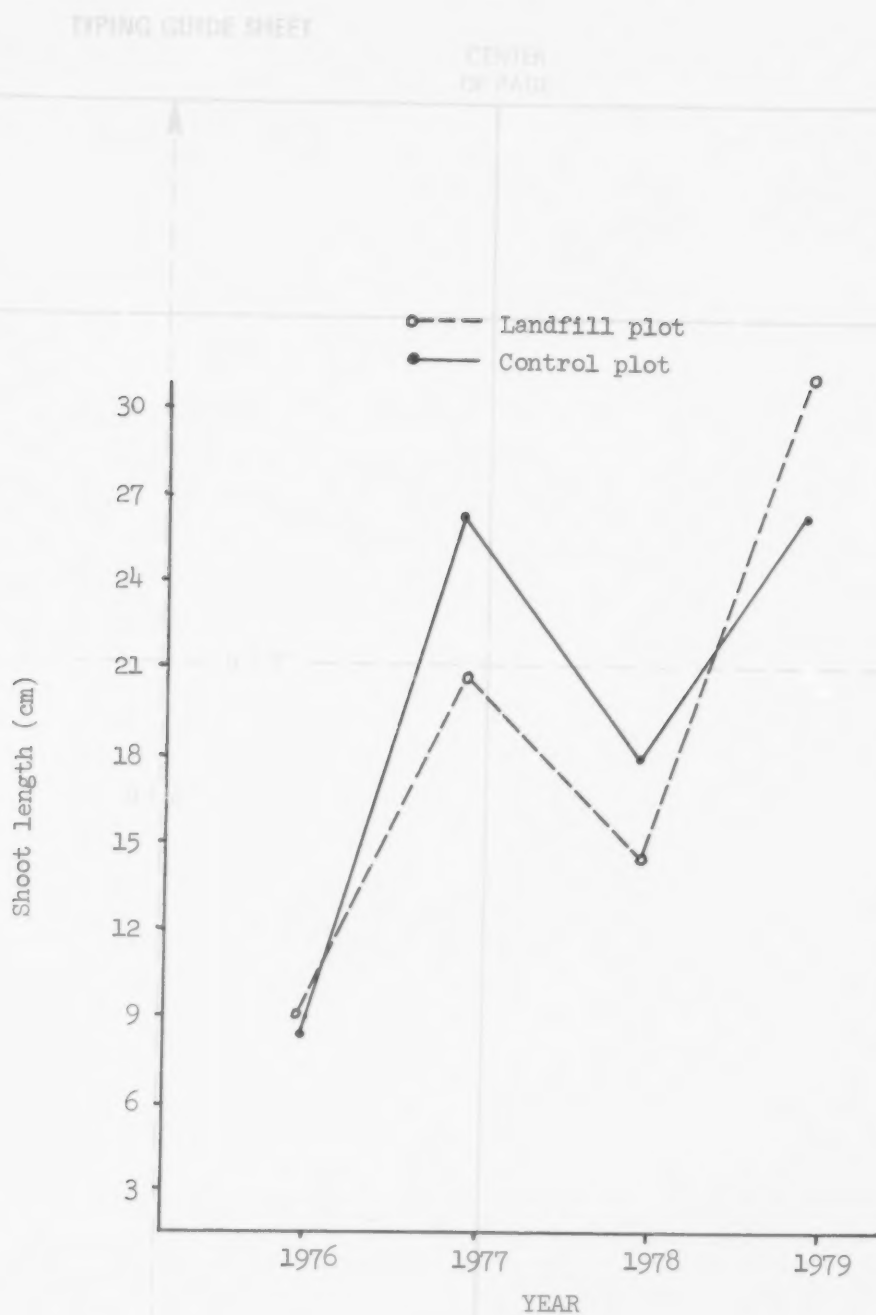


Figure A-1. Black gum shoot length on landfill and control plots from 1976 through 1979.

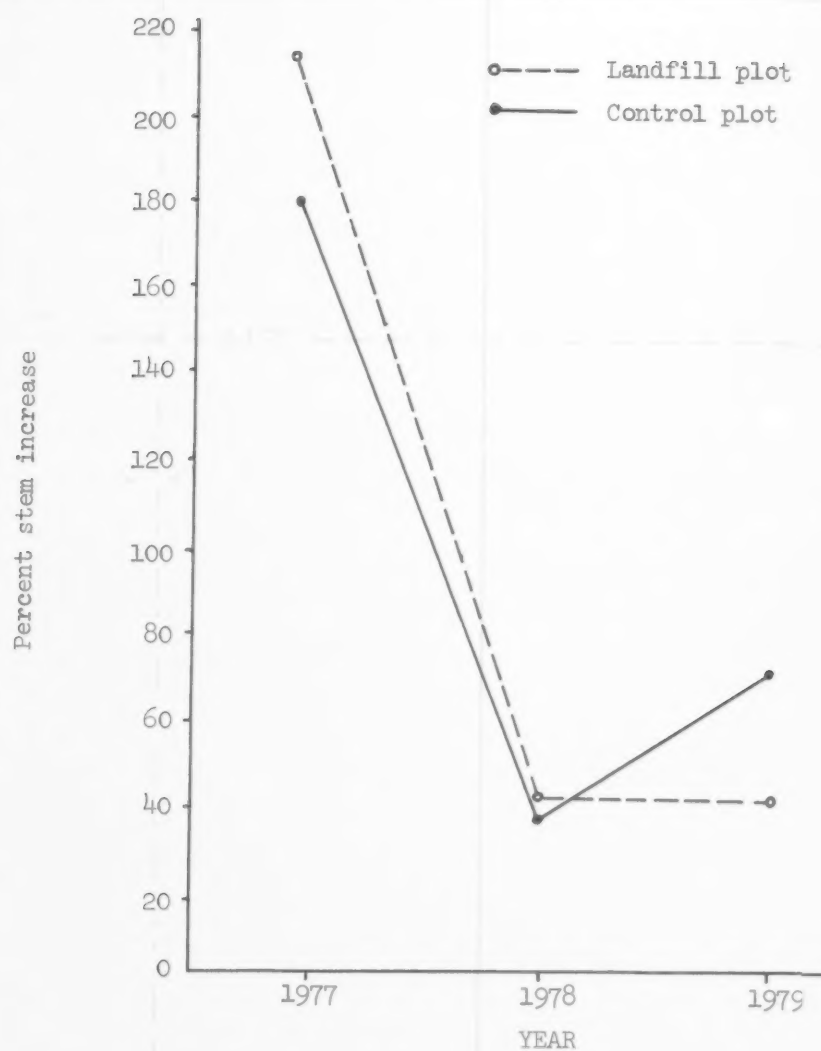


Figure A-2. Black gum percent stem increase during the years 1977 through 1979.

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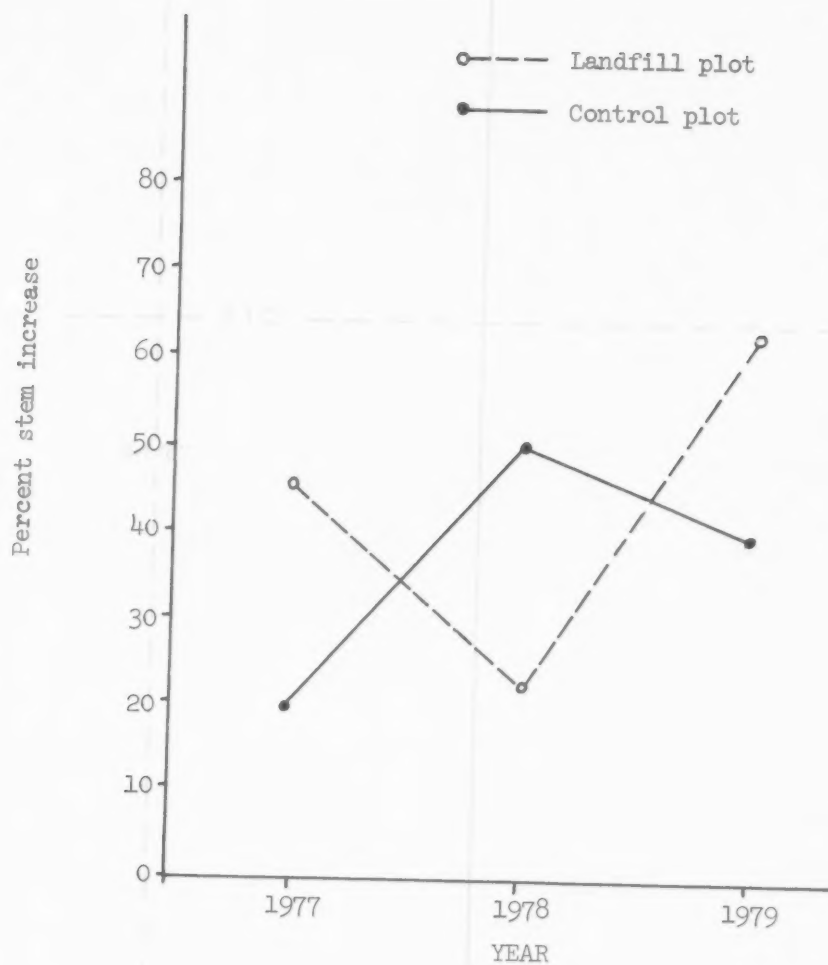


Figure A-4. Japanese yew percent stem increase during the years 1977 through 1979.

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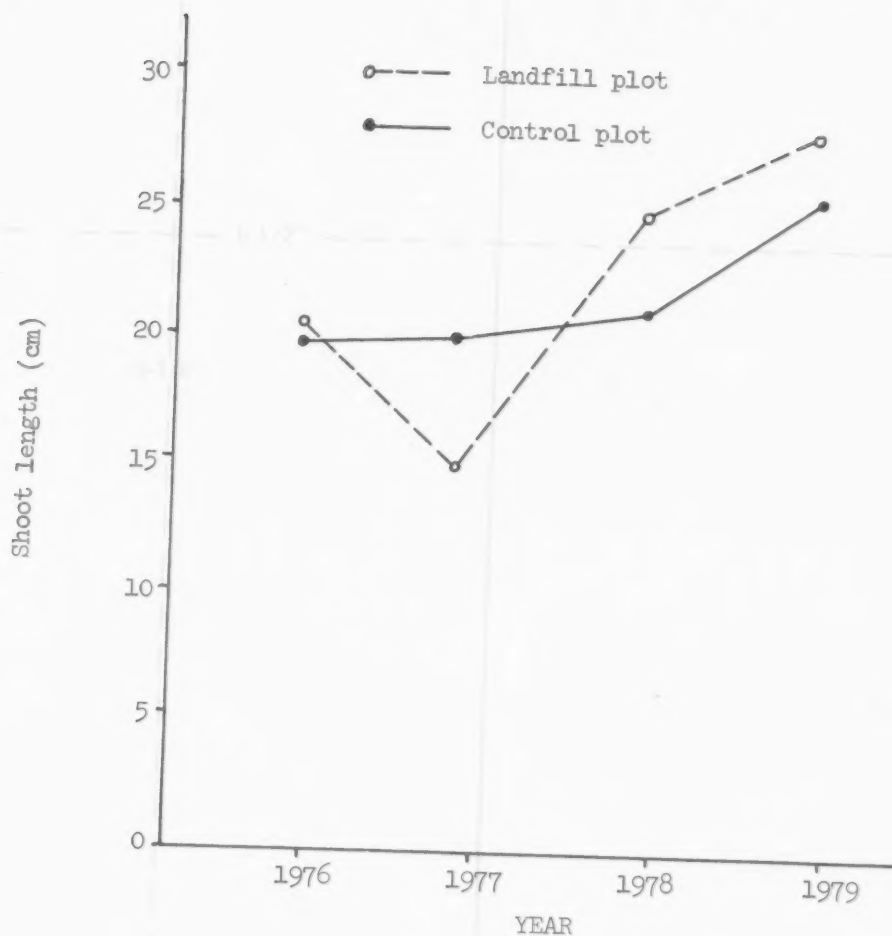


Figure A-5. Japanese black pine shoot length on landfill and control plots from 1976 through 1979.

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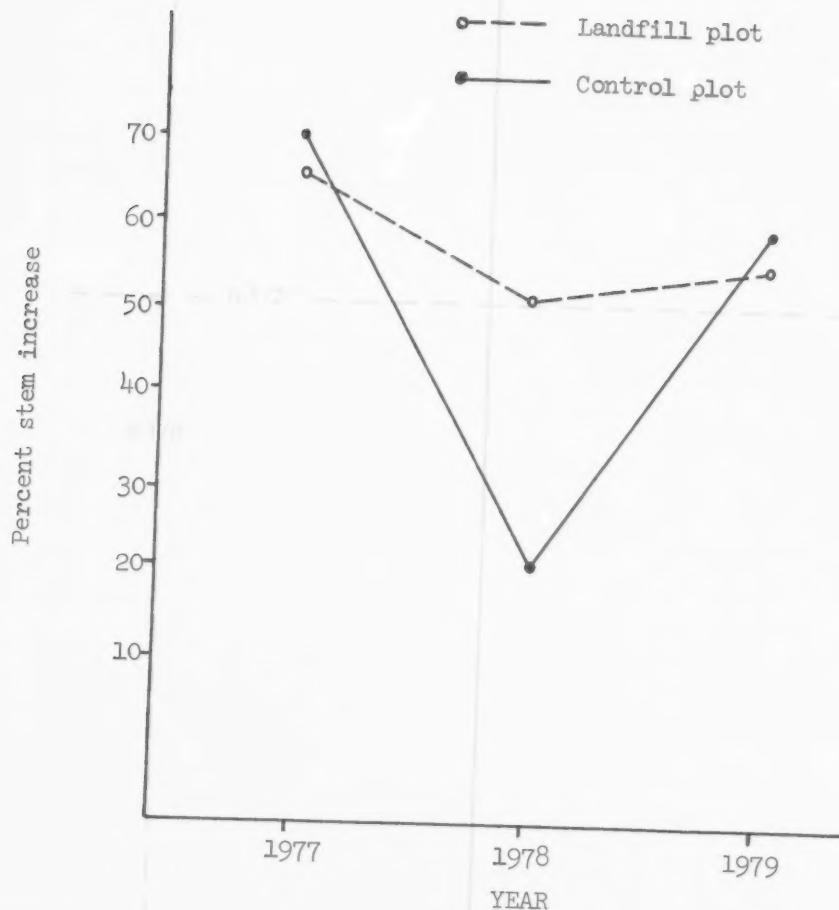


Figure A-6. Japanese black pine percent stem increase during the years 1977 through 1979.

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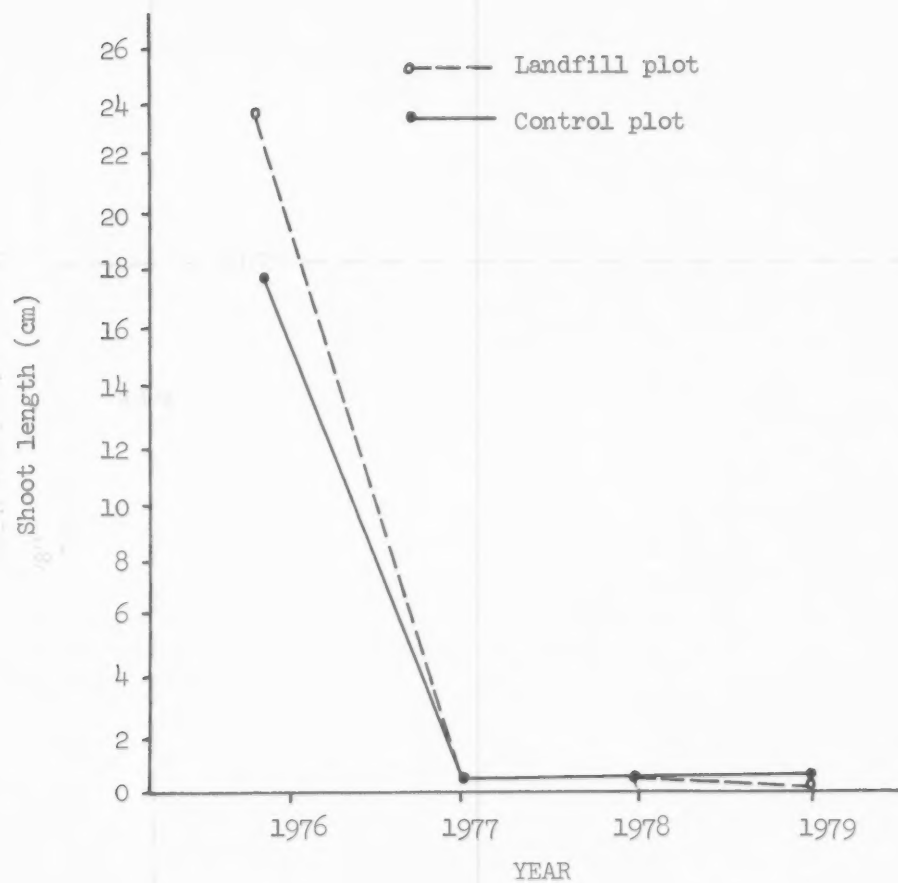
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Figure A-7. Ginkgo shoot length on landfill and control plots from 1976 through 1979.

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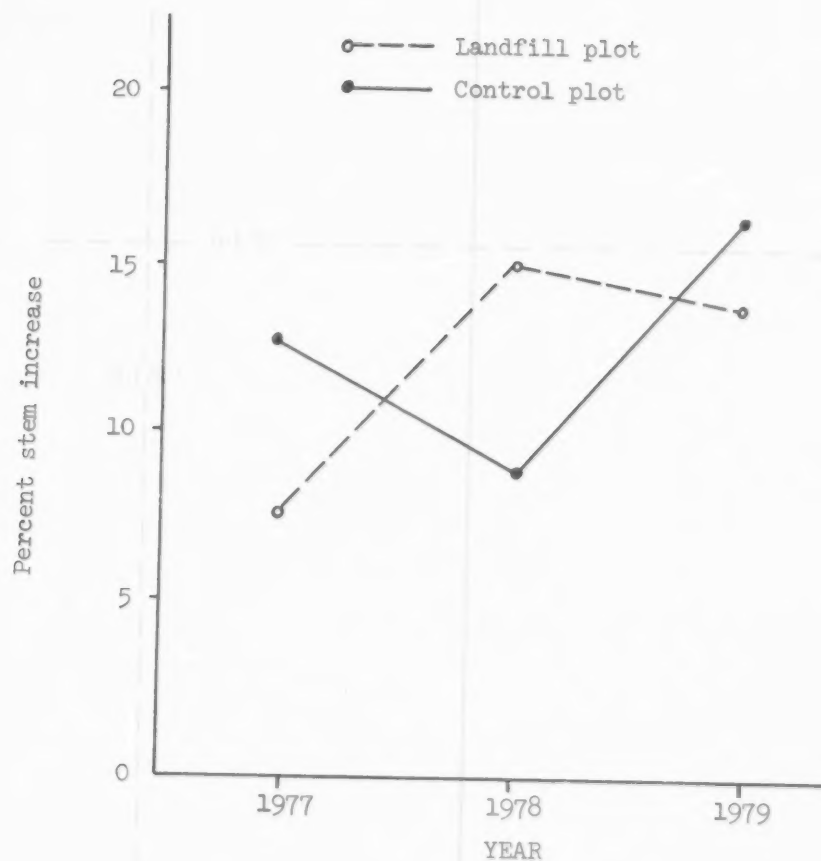
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Figure A-8. Ginkgo percent stem increase during the years 1977 through 1979.

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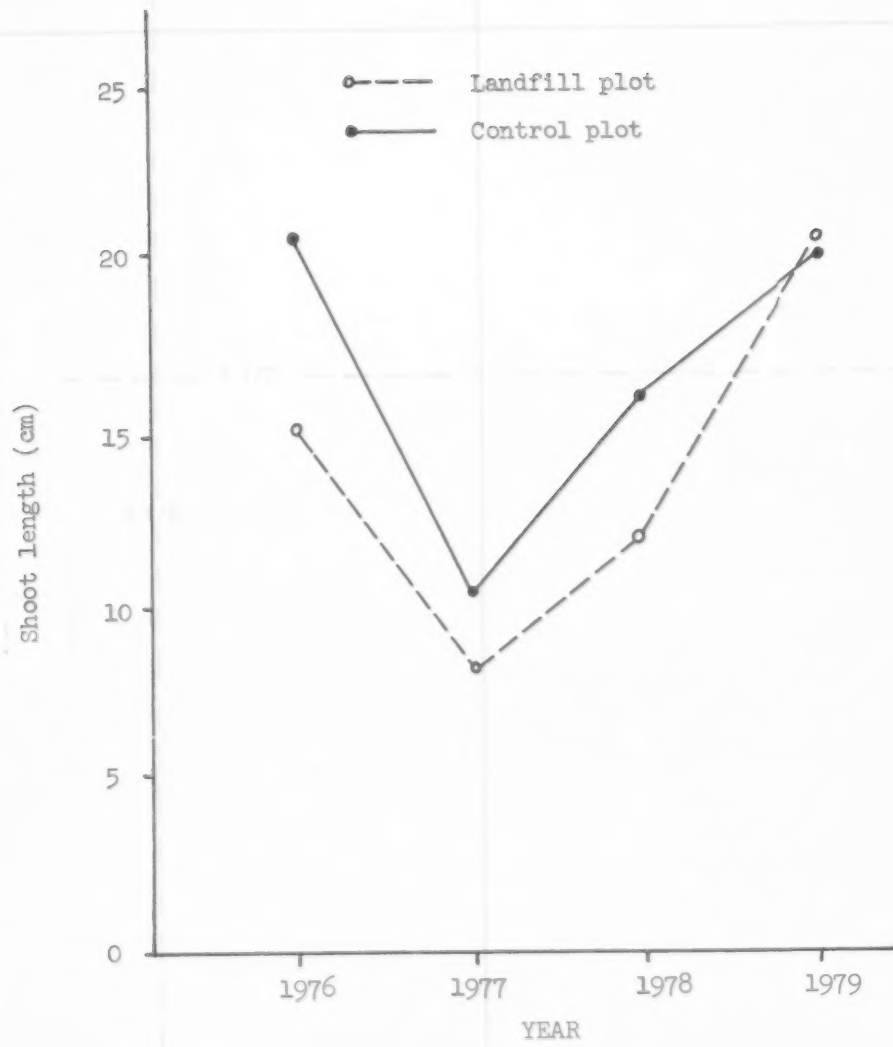


Figure A-9. White pine shoot length on landfill and control plots from 1976 through 1979.

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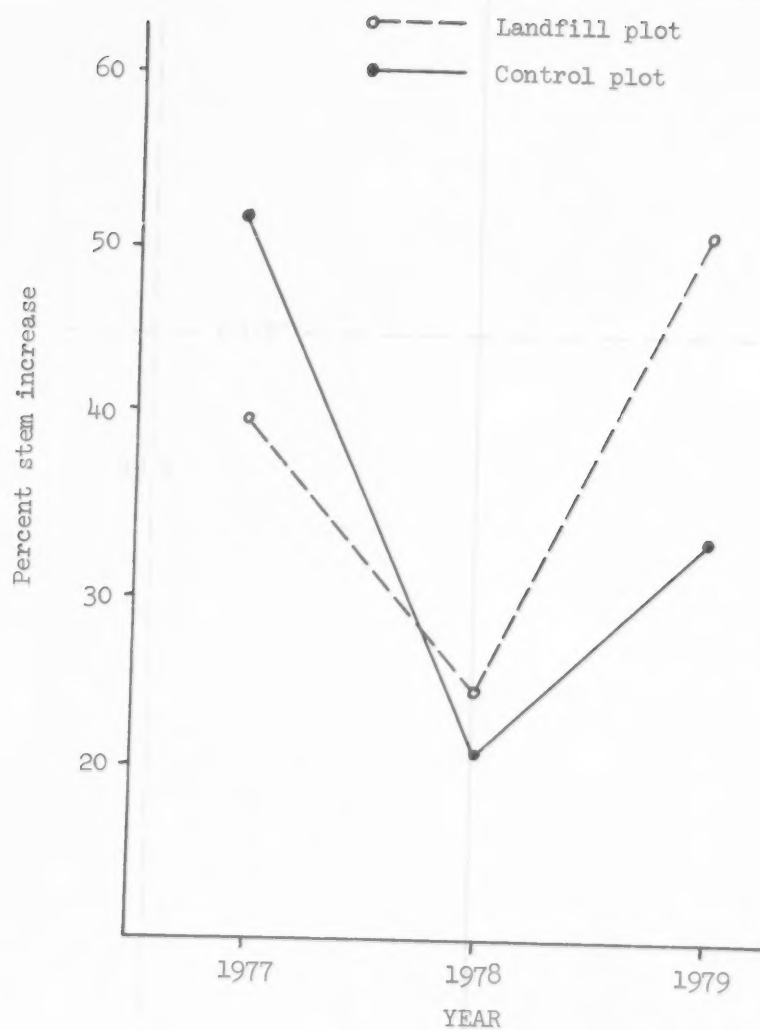


Figure A-10. White pine percent stem increase during the years 1977 through 1979.

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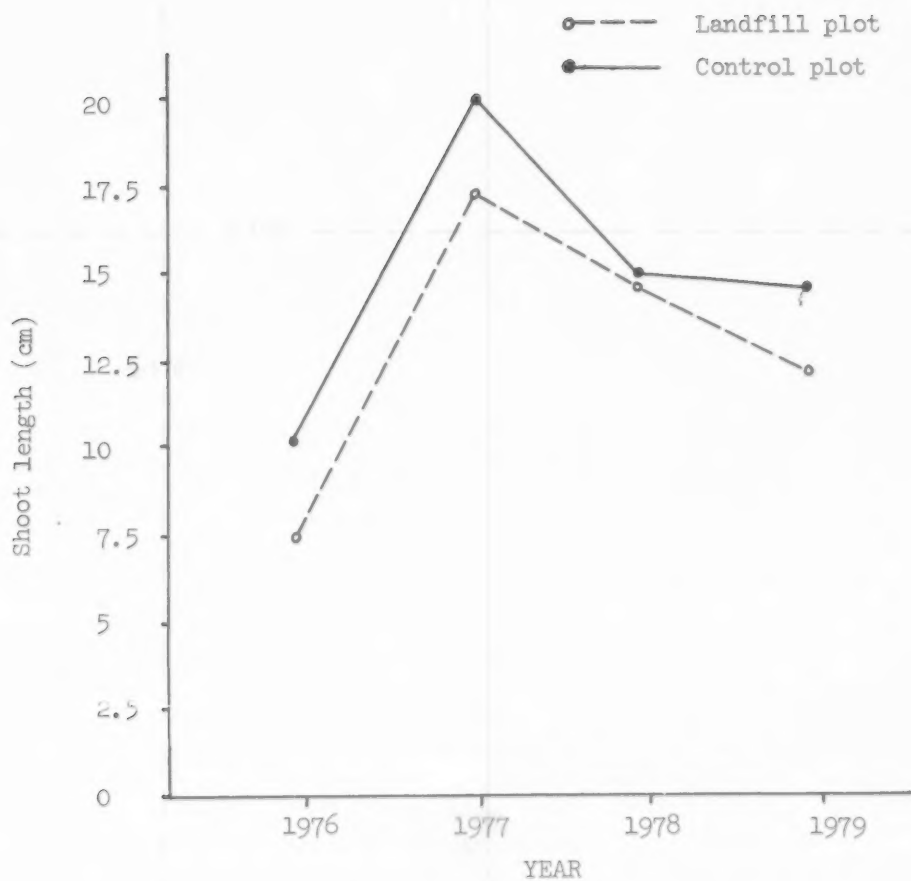


Figure A-11. Bayberry shoot length on landfill and control plots from 1976 through 1979.

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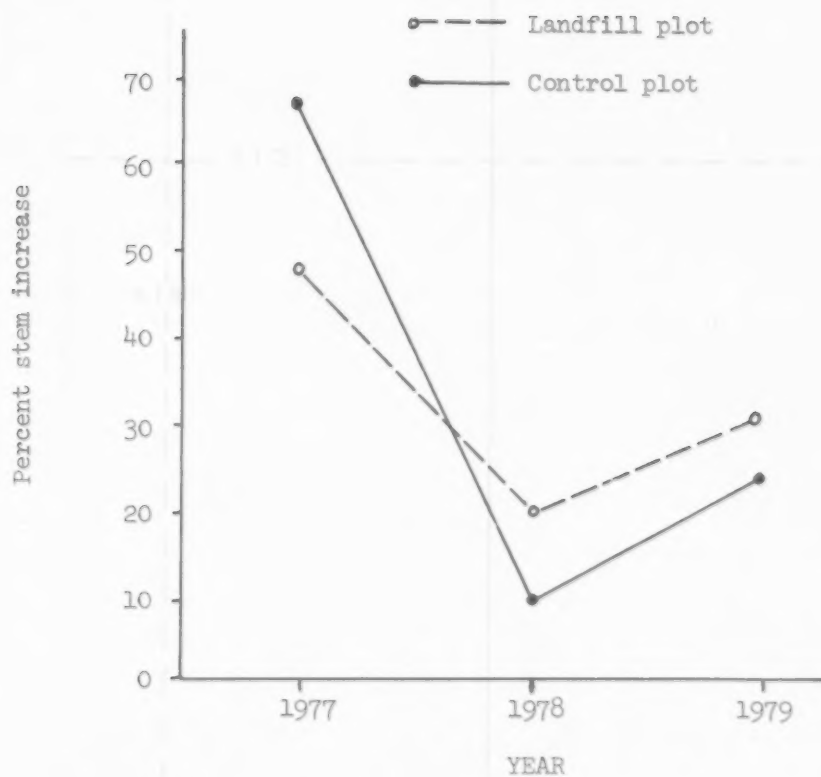


Figure A-12. Bayberry percent stem increase during the years 1977 through 1979.

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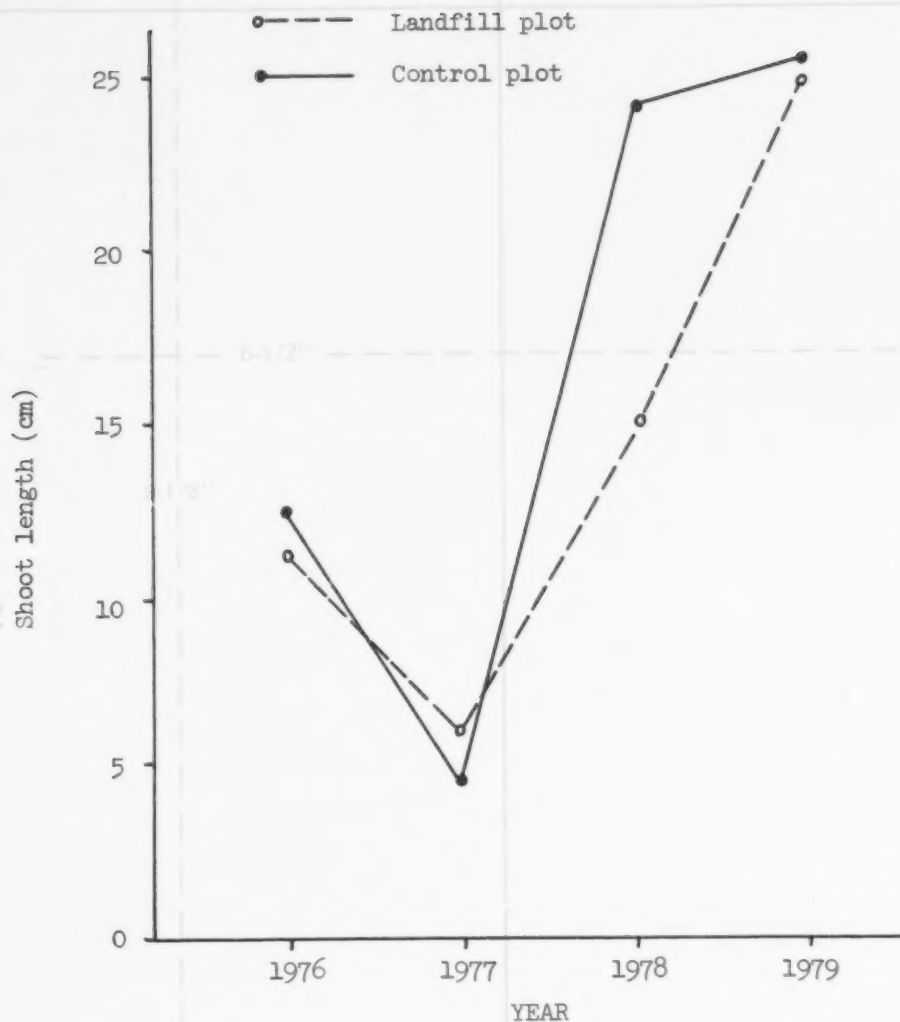


Figure A-13. Norway spruce shoot length on landfill and control plots from 1976 through 1979.

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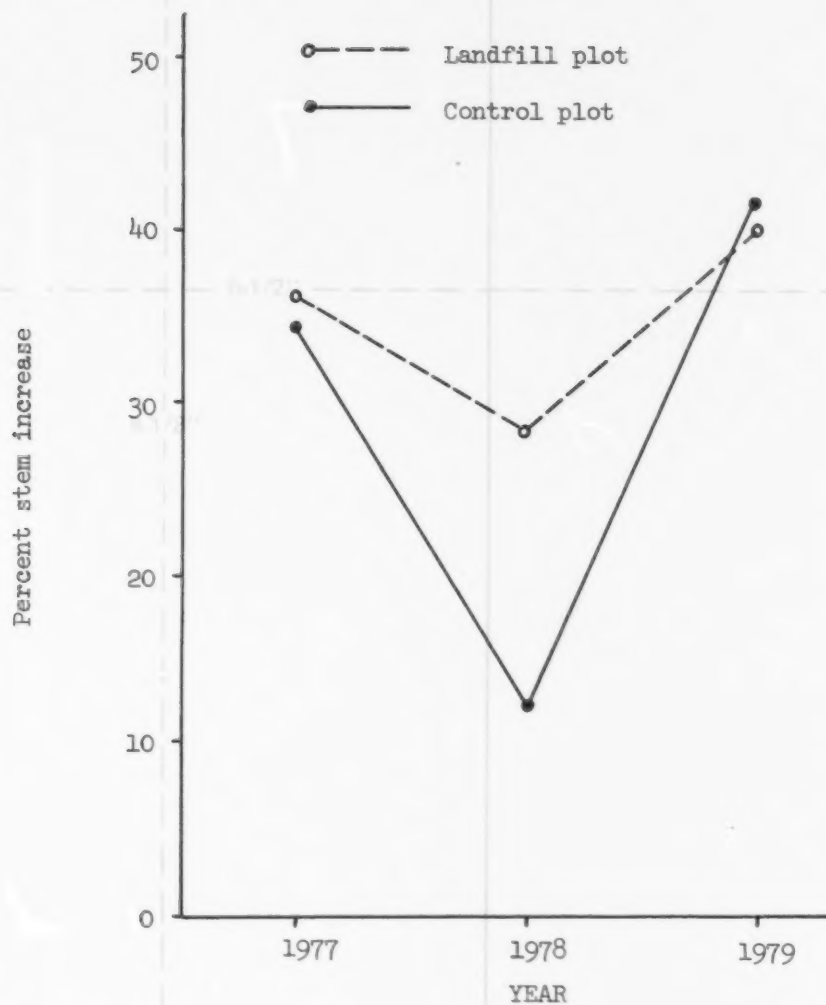


Figure A-14. Norway spruce percent stem increase during the years 1977 through 1979.

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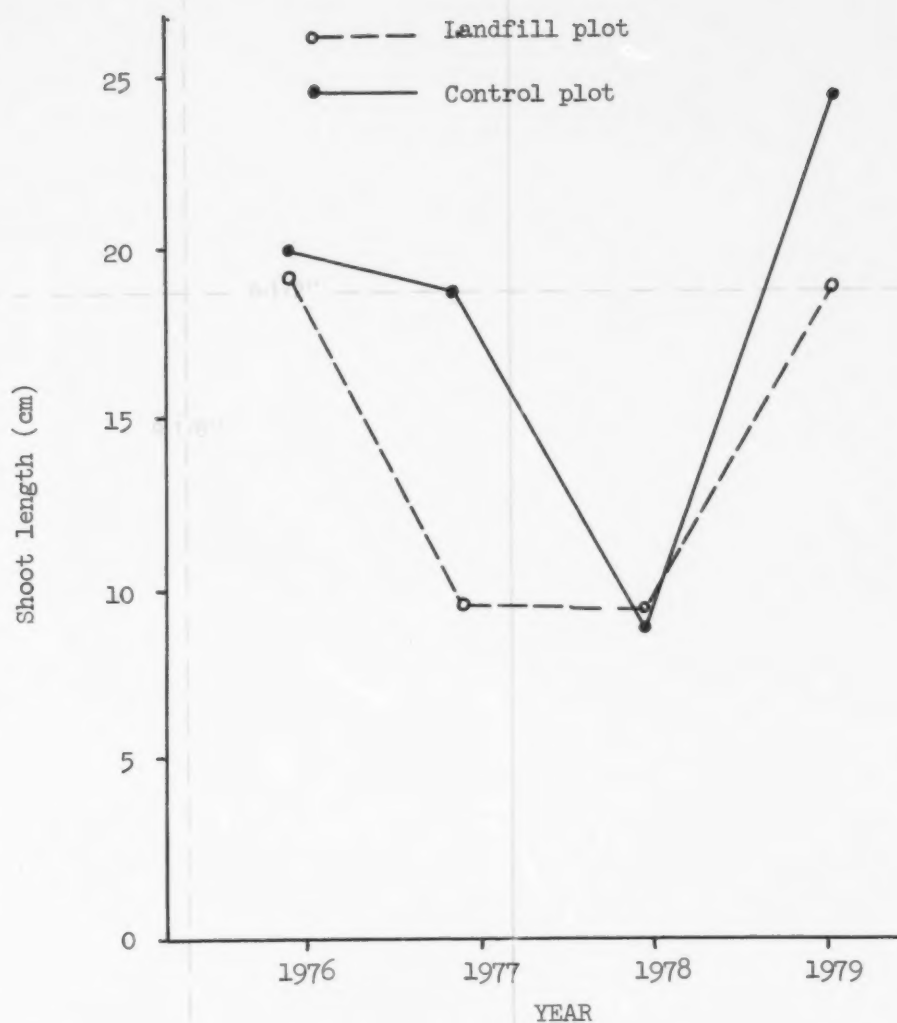


Figure A-15. American basswood shoot length on landfill and control plots from 1976 through 1979.

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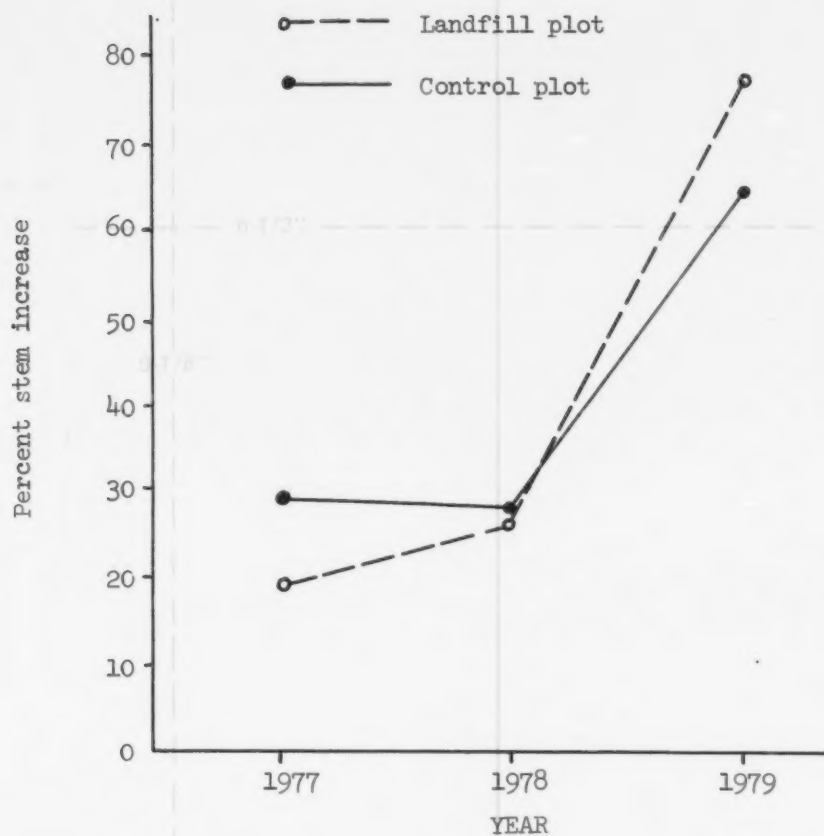


Figure A-16. American basswood percent stem increase during the years 1977 through 1979.

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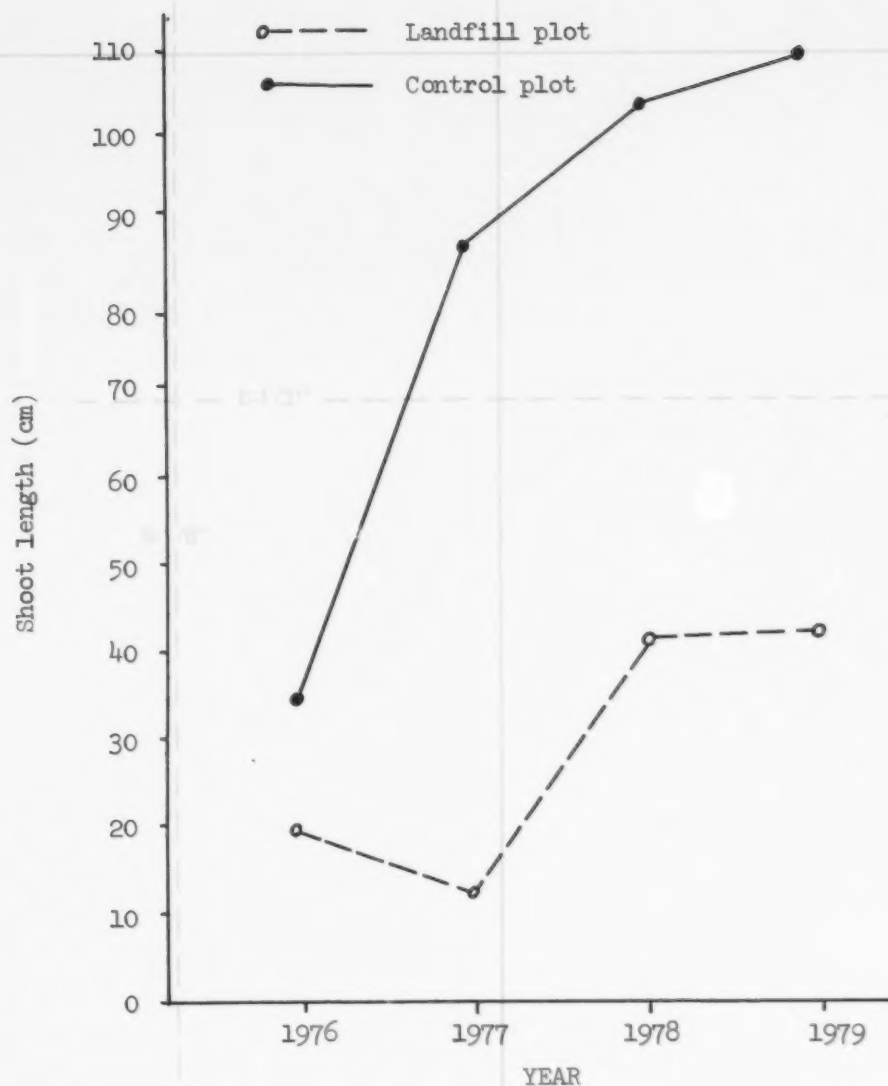


Figure A-17. Hybrid poplar shoot length on landfill and control plots from 1976 through 1979.

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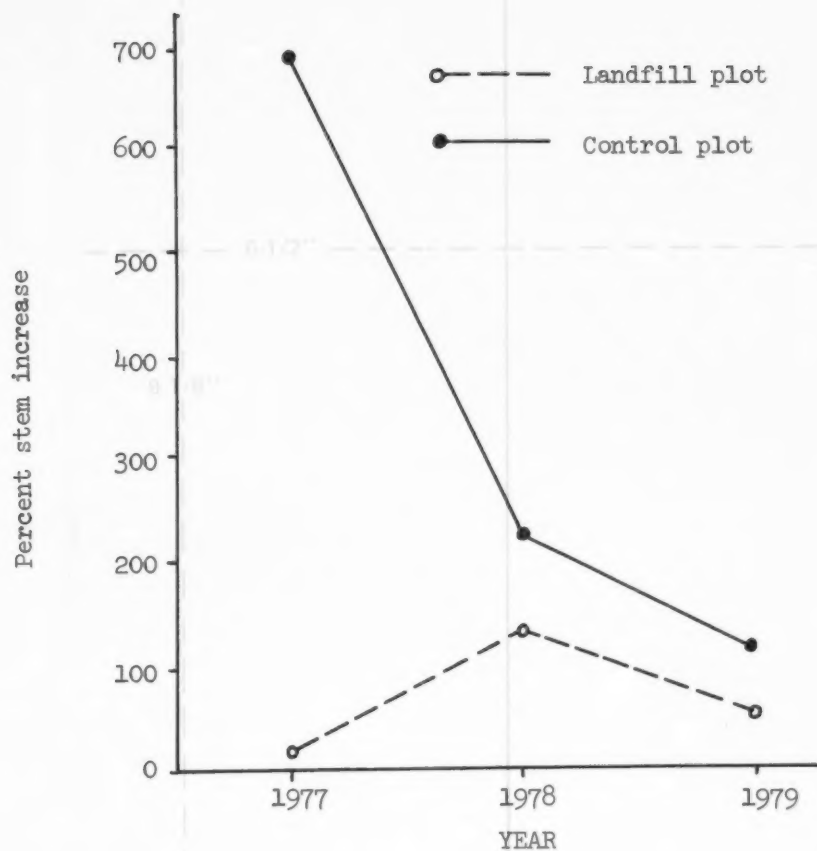


Figure A-18. Hybrid poplar percent stem increase during the years 1977 through 1979.

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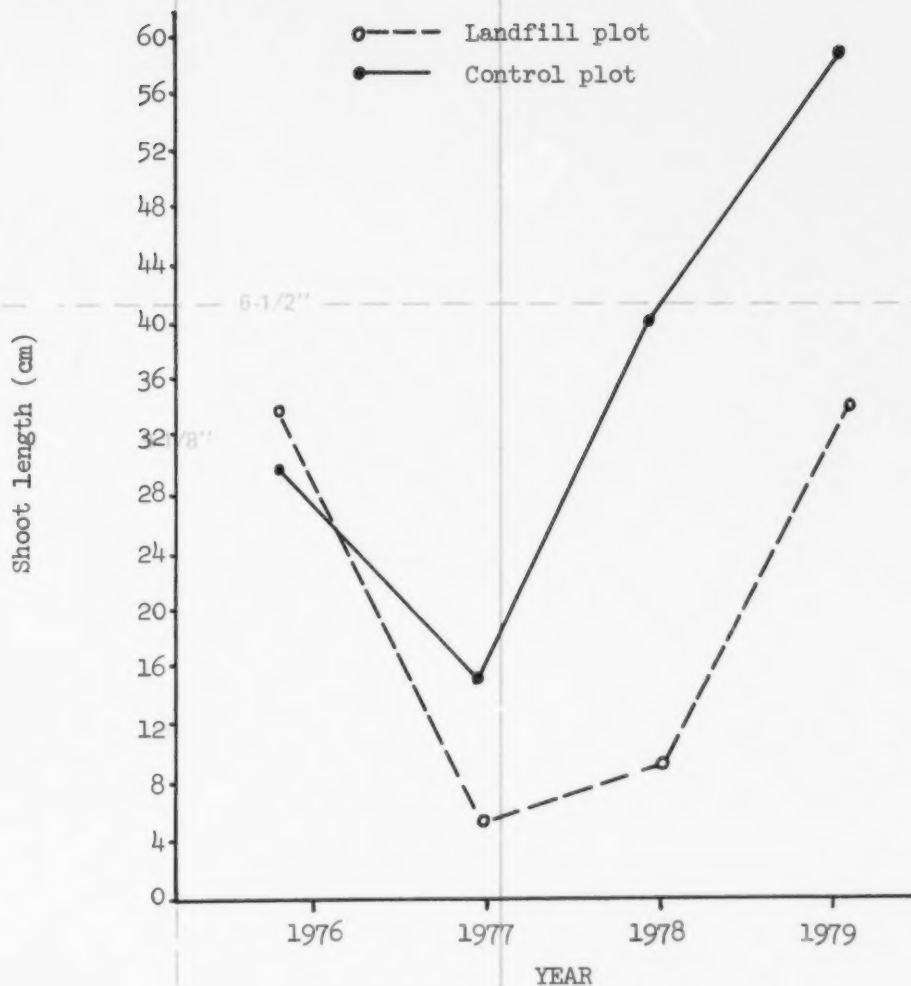


Figure A-19. Green ash shoot length on landfill and control plot from 1976 through 1979.

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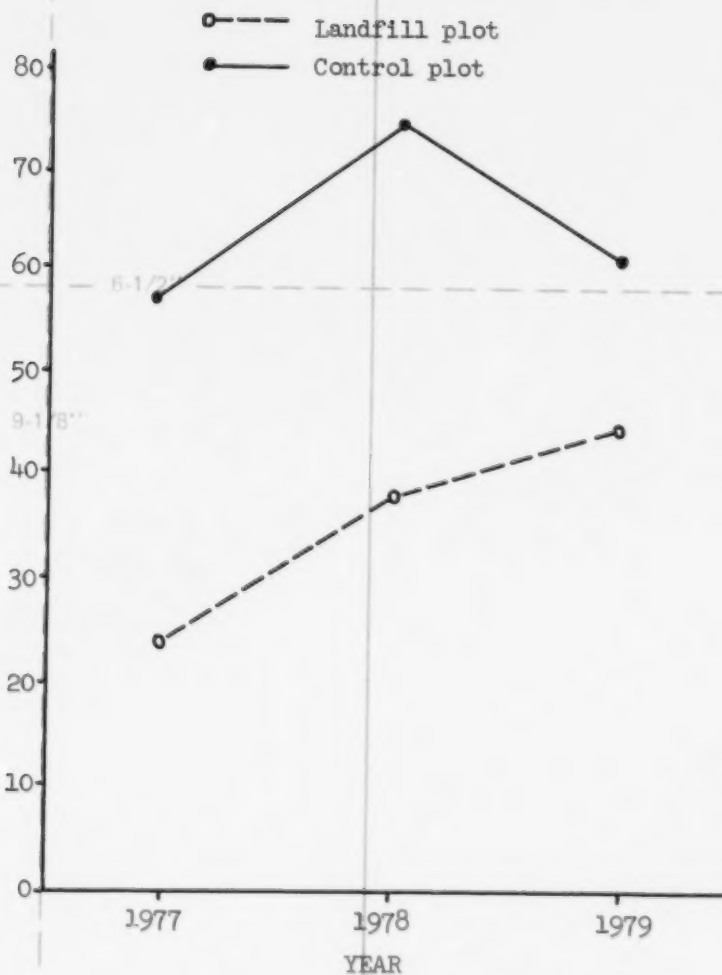


Figure A-20. Green ash percent stem increase during the years 1977 through 1979.

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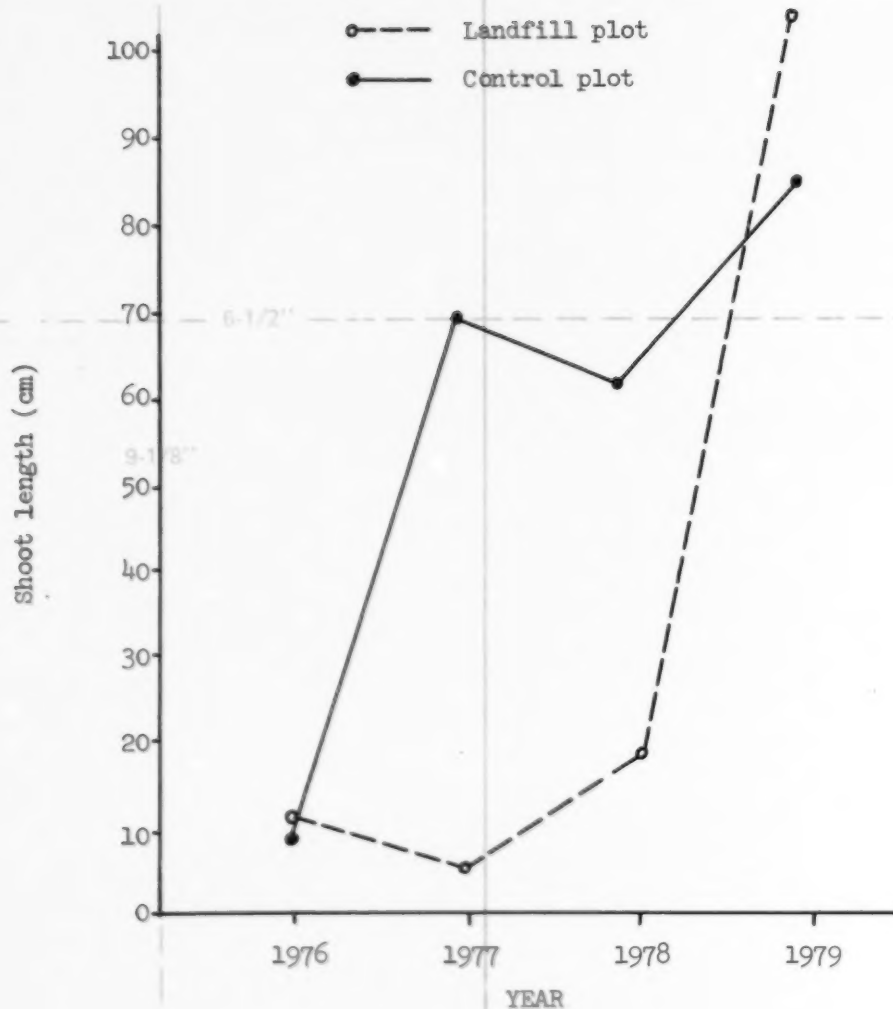


Figure A-21. Honey locust shoot length during the years 1977 through 1979.

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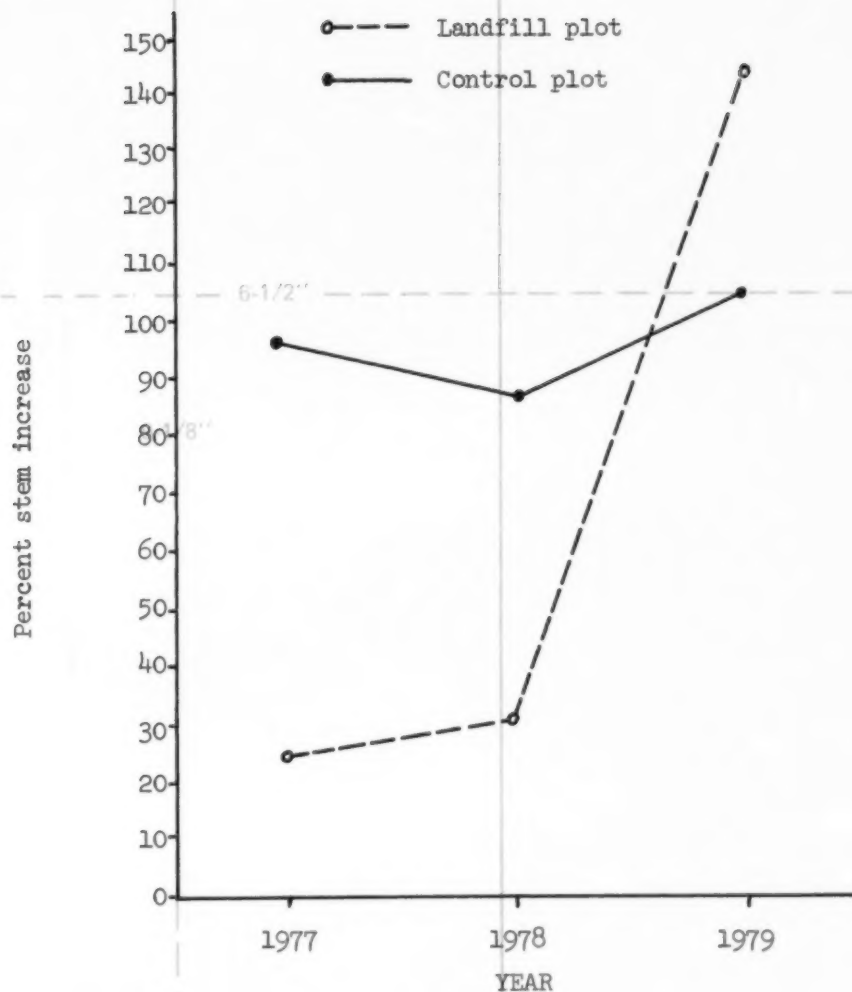


Figure A-22. Honey locust percent stem increase during the years 1977 through 1979.

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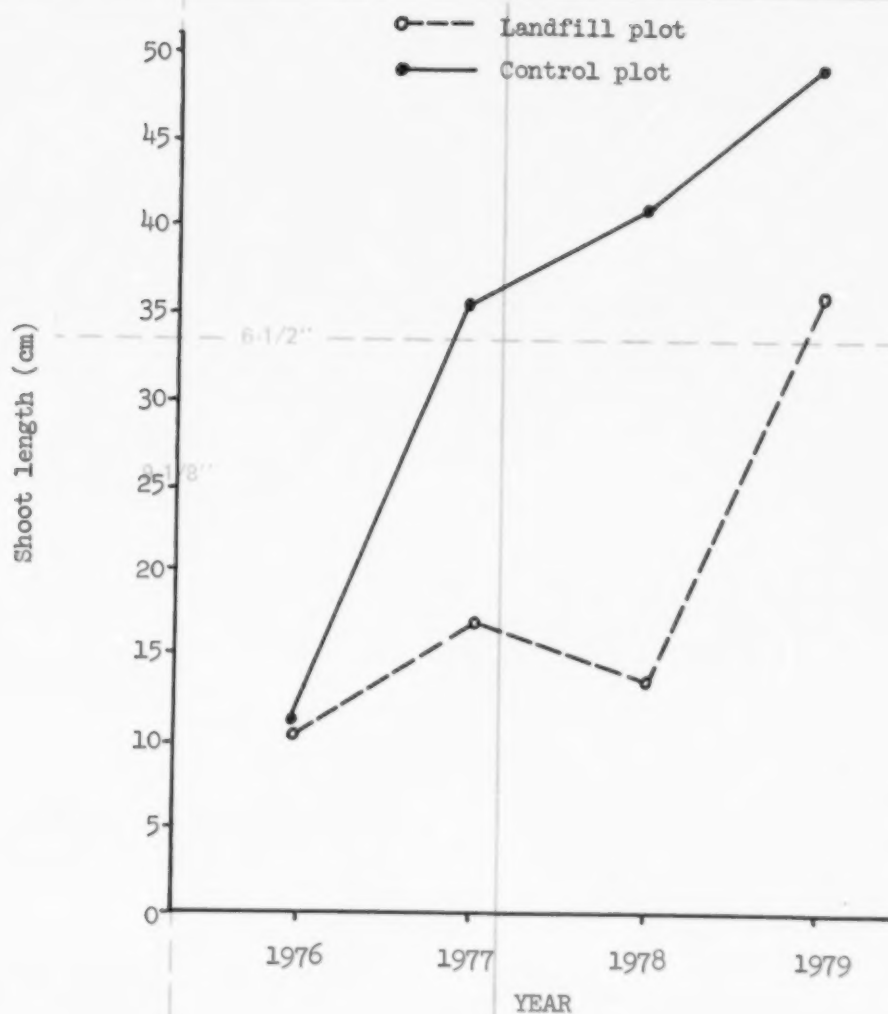


Figure A-23. Sweet gum shoot length on landfill and control plots from 1976 through 1979.

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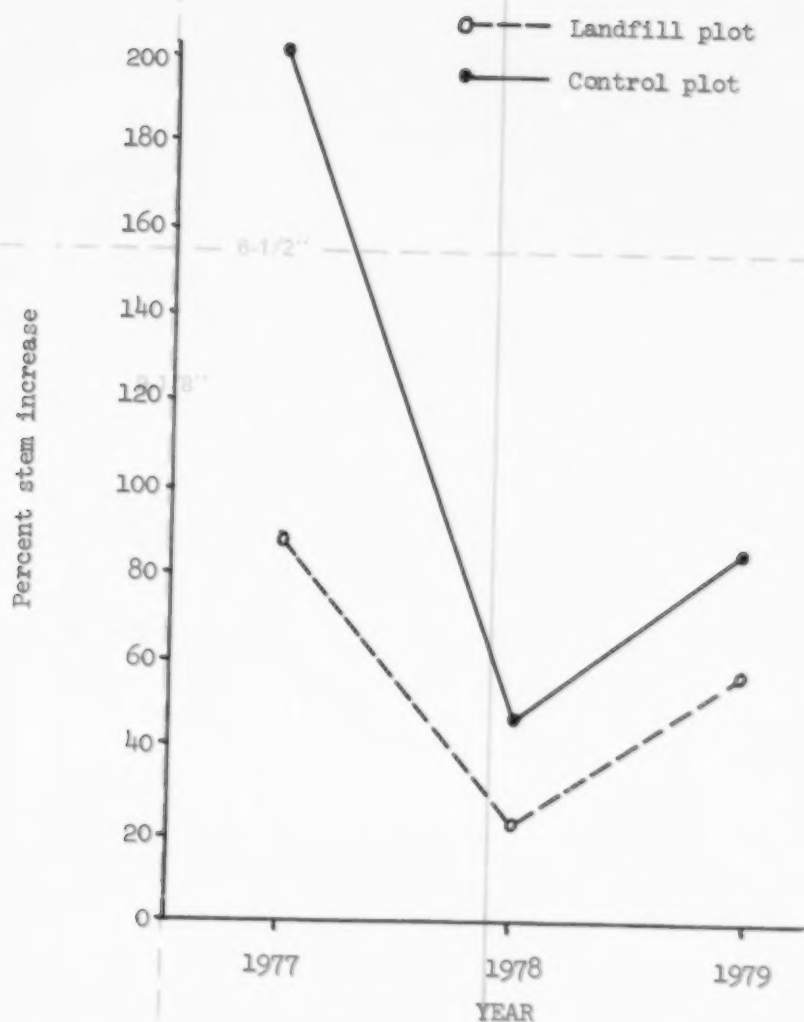


Figure A-24. Sweet gum percent stem increase during the years 1977 through 1979.

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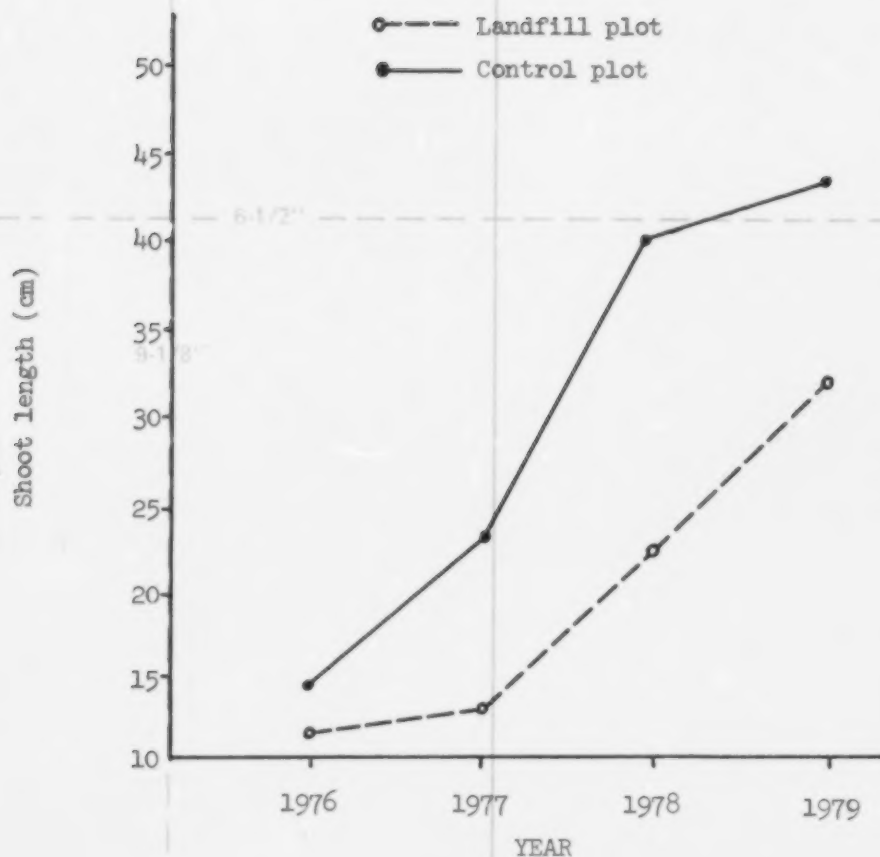


Figure A-25. Pin oak shoot length on landfill and control plots from 1976 through 1979.

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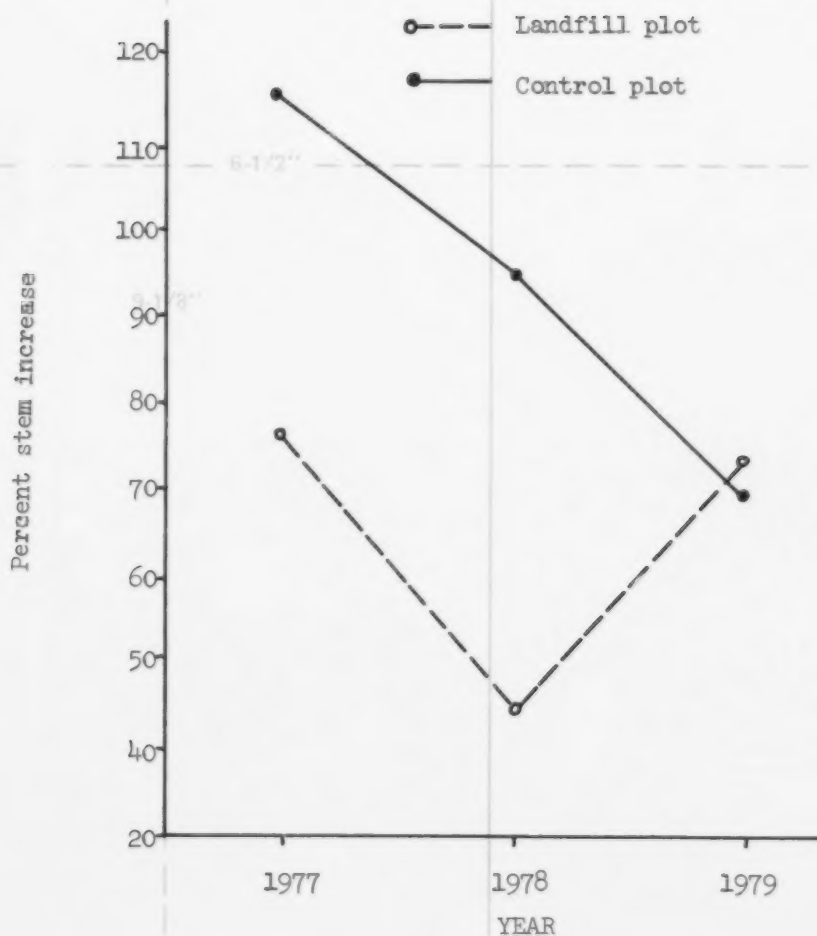


Figure A-26. Pin oak percent stem increase during the years 1977 through 1979.

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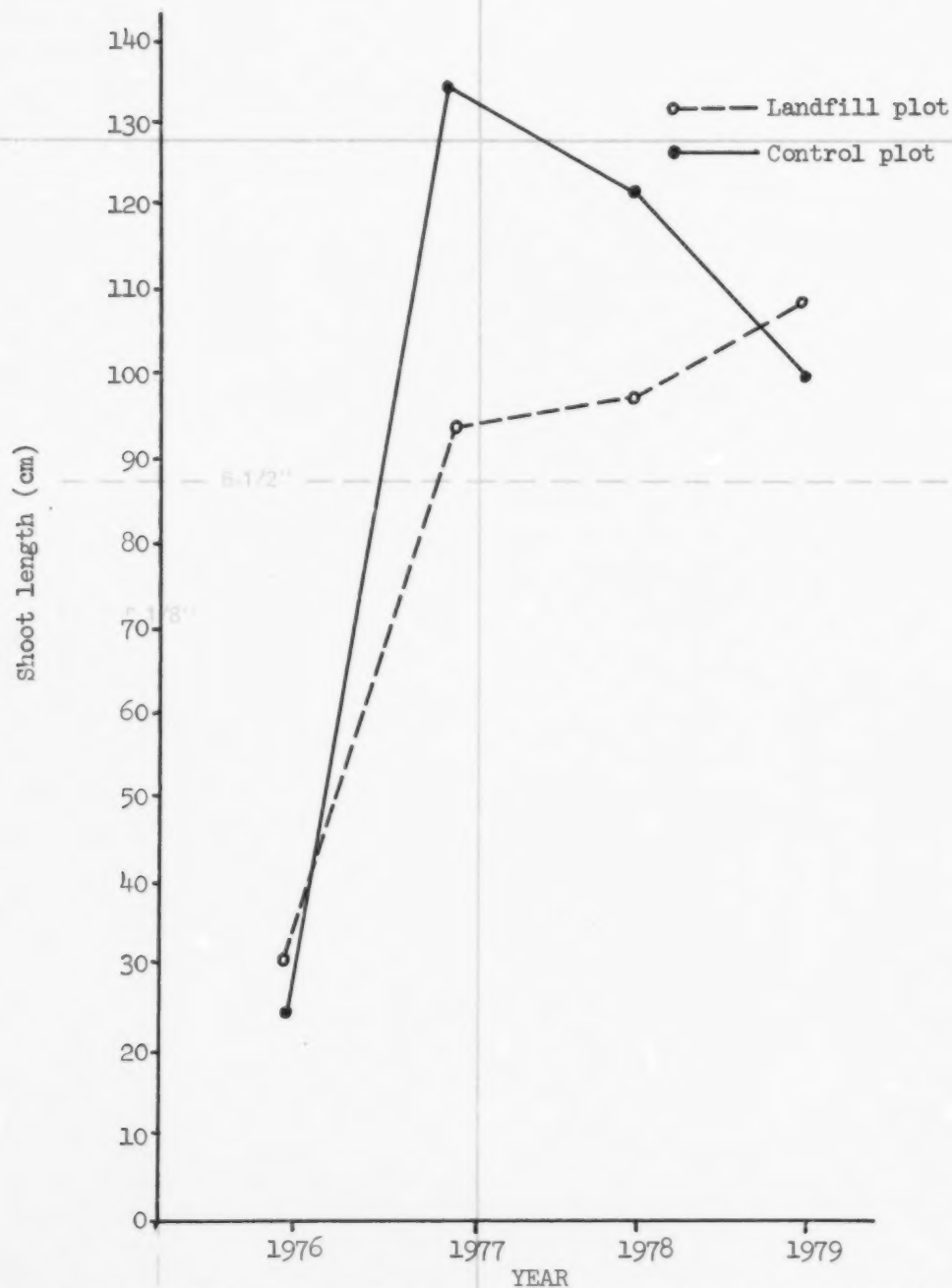


Figure A-27. Hybrid poplar rooted cuttings shoot length on landfill and control plots from 1976 through 1979.

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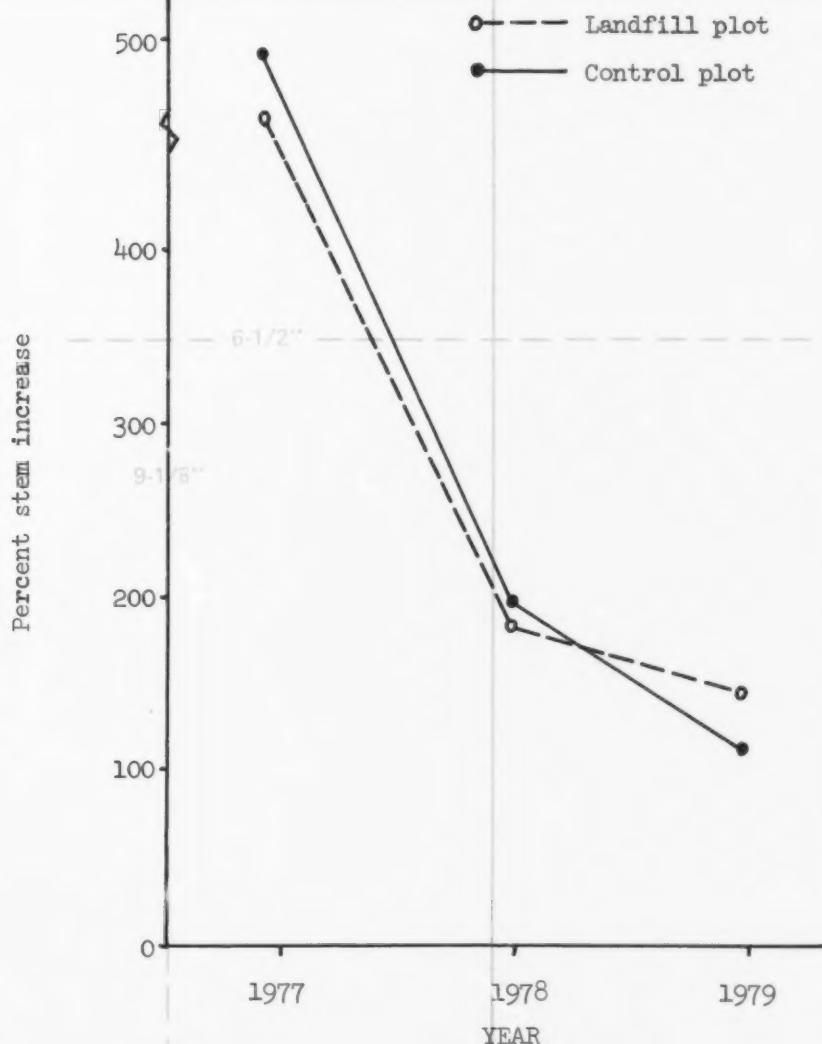


Figure A-28. Hybrid poplar rooted cuttings percent stem increase during the years 1977 through 1979.

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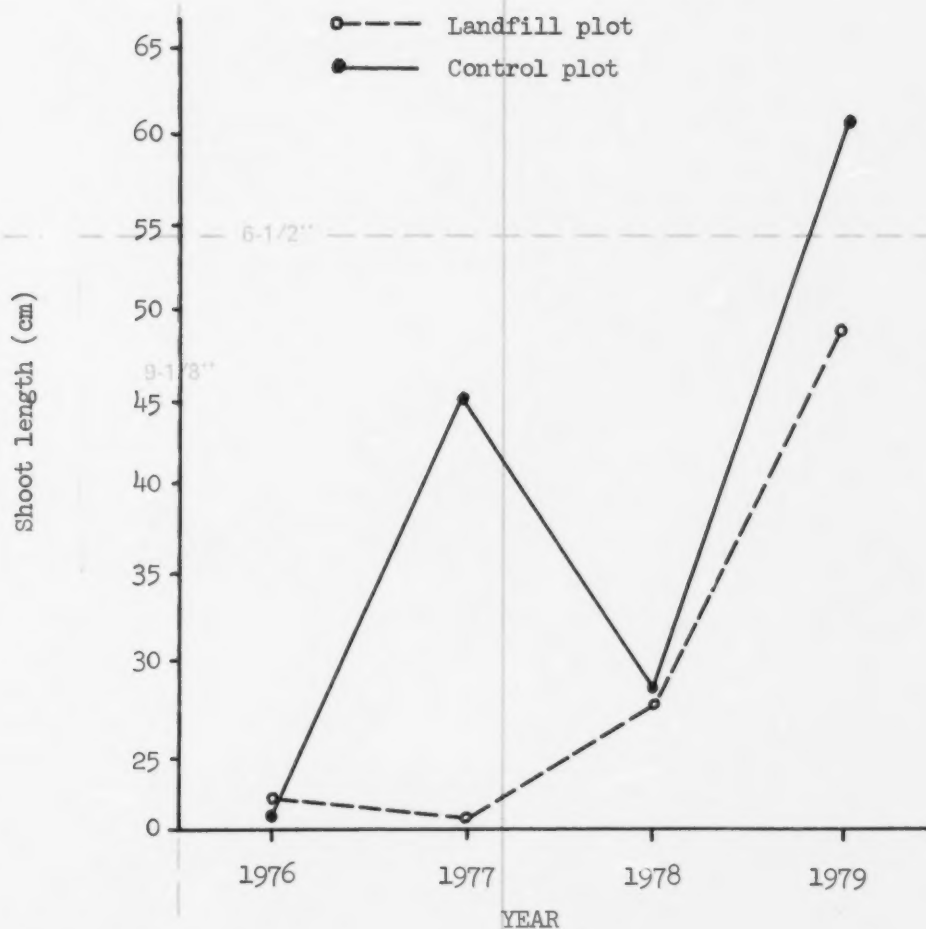


Figure A-29. Red maple shoot length on landfill and control plots from 1976 through 1979.

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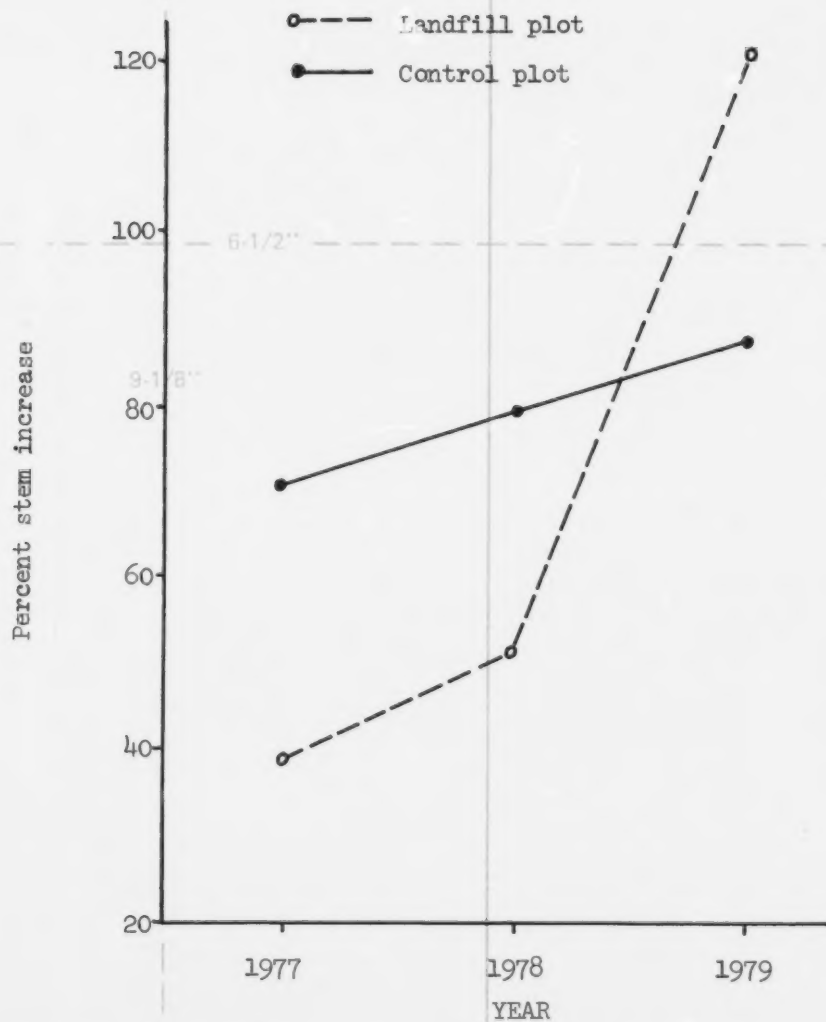


Figure A-30. Red maple percent stem increase during the years 1977 through 1979.

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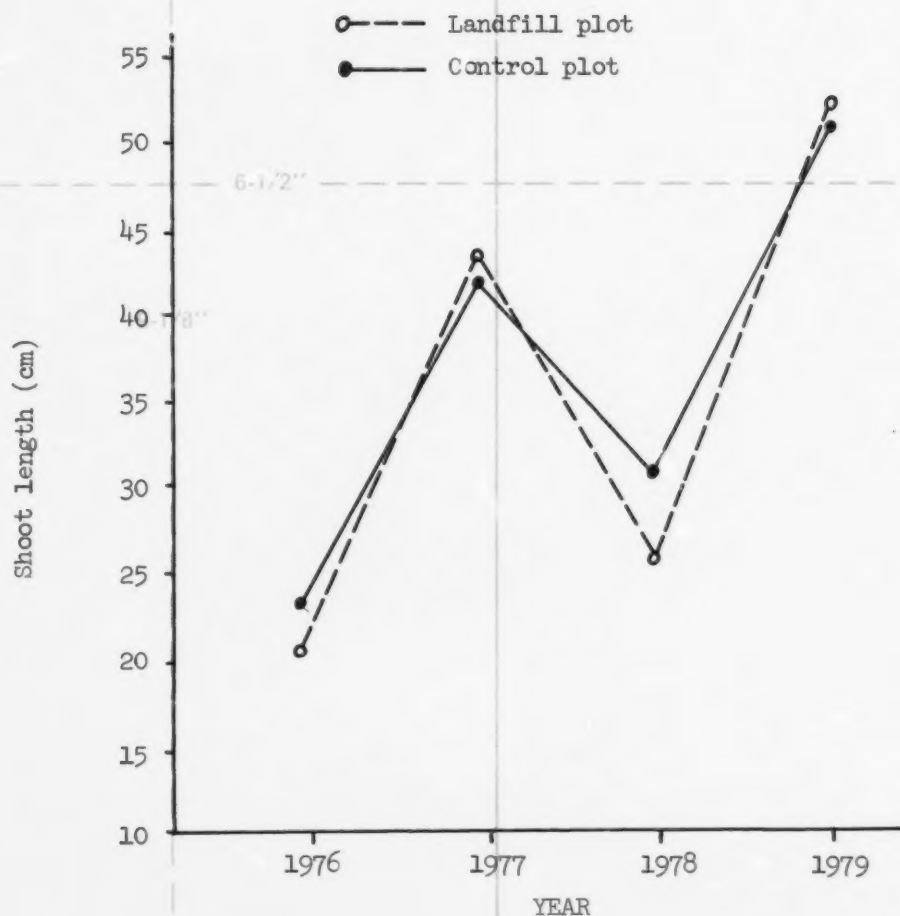


Figure A-31. American sycamore shoot length on landfill and control plots from 1976 through 1979.

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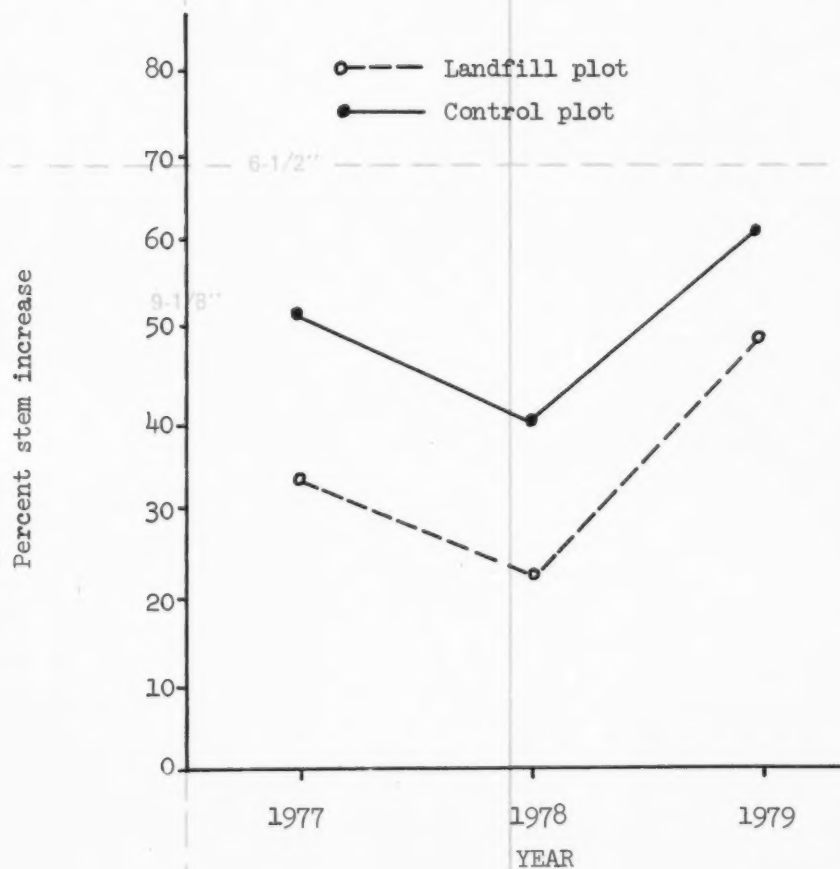


Figure A-32. American sycamore percent stem increase during the years 1977 through 1979.

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APPENDIX B

CORRELATION COEFFICIENTS (r) OF SOIL PARAMETERS WITH FOUR GROWTH MEASUREMENTS

	Shoot length	Leaf weight	Root biomass	Stem area increase
O ₂	+0.50*	+0.37*	+0.33*	+0.48*
CO ₂	-0.55*	-0.41*	-0.37*	-0.51*
K (Oct.)	+0.43*	+0.43*	+0.33*	+0.50*
Mn (June)	+0.53*	+0.48*	+0.23*	+0.61*
Diff. in Mn (June - Oct.)	+0.65*	+0.59*	+0.27	+0.73*
NO ₃ (Oct.)	+0.60*	+0.64*	+0.58*	+0.54*
Moisture content	+0.02	+0.03	+0.37*	+0.08
Bulk density	+0.59*	+0.64*	+0.58*	+0.54*

*Significant @ P<.05.

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APPENDIX C

SIGNIFICANT SOIL PARAMETERS IN THE REGRESSION EQUATIONS FOR DETERMINATION OF
BASSWOOD NUTRIENT CONCENTRATION

Nutrient	Regression parameters				
	B_0	B_1	B_2	R_2	P level
Manganese	-0.1	+0.3 oxygen		67%	<.01
Iron	-2.5	+0.1 highest temperature		57%	<.02
Potassium	2.0	+0.05 oxygen		36%	<.08
Magnesium	1.2	+0.01 oxygen		36%	<.08
Calcium	7.8	-0.07 highest temperature		78%	<.01
Zinc		No significant effects			<.10
Copper	0.3	+0.003 highest temperature		48%	<.04
Nitrogen	3.2	+0.05 oxygen	-0.006 bulk density	84%	<.05

Legend: B_0 = Y intercept, B_1 = Regression Coefficient, B_2 = Regression Coefficient, R_2 = Coefficient of Determination.

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